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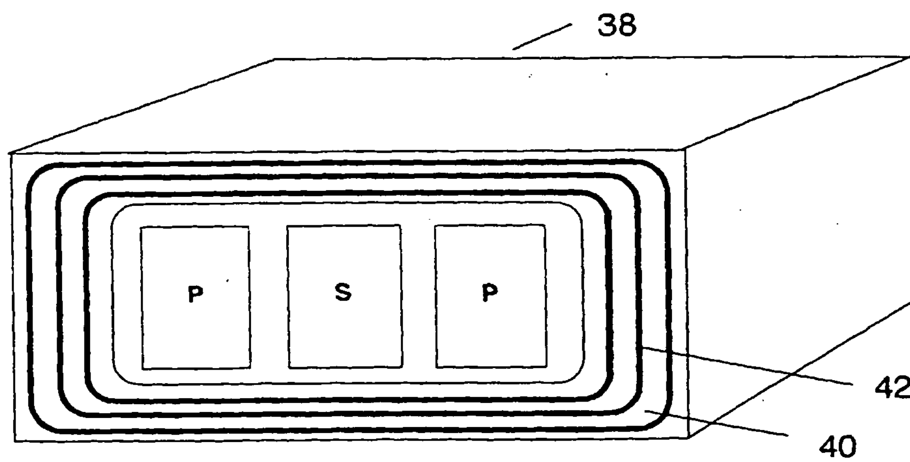
(54) Title: PLANAR MINIATURE INDUCTORS AND TRANSFORMERS AND MINIATURE TRANSFORMERS FOR MILLI-MACHINED INSTRUMENTS



(57) Abstract: This invention relates to the planarization of inductive components by reducing standard coiled designs to single turn designs from which the required parameters are obtained by scaling the length. Single turn designs having magnetic material (24) encircling the conductors (18, 20, 22) along their full length enable the thinnest form. The single turn form also enables the inductive component to be routed according to any shape in the plane or on any conformal surface. The single turn inductors do not need to coil hence there is no overlap necessary in the plane. The planar form allows integration of inductive components with integrated circuits. These inductive components can be embedded in other materials. They can also be fabricated directly onto parts. The differential current transformer by virtue of its fabrication next to a capacitive pick-off enables the preservation of the purity of the signal obtained by taking signal differences close to the transducer and minimizing pick-up from leads.

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PLANAR MINIATURE INDUCTORS AND TRANSFORMERS AND MINIATURE TRANSFORMERS FOR MILLIMACHINED INSTRUMENTS

Statement of Federally Sponsored Research and Development

This invention was made with Government support under contract number DTRA01-99-C-0186 awarded by BMDO. The Government has certain rights in the invention.

Field of the Invention

This invention relates to planar miniature inductors and transformers, and miniature transformers for millimachined instruments.

Background of the Invention

Miniature Transformers for Millimachined Instruments – a Pick-off Application

There are families of sensors such as gyros and accelerometers which require the angle measurement of a rotating member for their output. A schematic representation of a typical rotating member 210 is shown in Figure1 in a differential arrangement of capacitive plates 211.

Capacitive sensors are used because of their low noise characteristics, size, stable dimensions, and potentially very small gaps. Noise levels on the order of 10 nano-radians at a bandwidth of 100 hertz are possible.

The major limiting factor in the performance of capacitive pick-offs is the effects of stray capacitance pickup on the electronic circuitry which handles the rotation signal. This is particularly true when the capacitive values are on the order of a few pico-farads as they are in small gyros and accelerometers fabricated by micro- and milli-machining technologies. A solution is to couple the capacitive transducer 212 to a differential transformer 213. The capacitor

pairs are tied in parallel with outputs connected to opposite ends of a transformer primary with a center tap to ground.

Traditional approach to planar transformers

Planar inductive components fabricated in multi-layered fashion have been published in the MEMS literature. Figure 2 shows in exploded view a multi-layered design for a toroidal concept 10 which is typical for the state-of-the-art. Coil windings 14 are wound about the magnetic core 11 (thin circular flat ring). Separating the coils from the core are insulating layers 12, 13. For the toroid requiring magnetic laminations, the core is formed from multiple flat rings separated by non-magnetic, insulating layers. Note that the coil windings require electrical connections between the top 15 and bottom 16 segments.

The difficulties with this approach are numerous and relate to the practicality of fabrication:

a. The number of coil turns is limited by the diameter of the ring core and the ability of the fabrication process to fabricate high aspect ratio vertical coil segments.
b. The alignment requirement to connect the top and bottom segments of the coil about the core needs to be extremely precise, given the small dimension of the conductor cross-section, in order to prevent shorts and opens.
c. The connection quality between top and bottom segments of the coil becomes a significant source of electrical resistance when considering the large number of turns that may need to be connected.
d. The possibility for an open connection at one of the coil interfaces is large and renders the component unusable.
e. Leakage flux occurs since the coil turns do not totally enclose the magnetic core.
f. In the case of the DCT transformer, the difficulty in carrying out the coil construction makes it difficult to match the primary turns.

Successful fabrication of this design would require very high precision, high aspect ratio equipment and processes with very high yield risk because only one short or one open renders the component useless. The high yield risk becomes even more impractical when considering integration with ICs and packaging.

Summary of the Invention

Planar Inductive Components

This invention addresses planar inductive components based on a linear, thin design topology that enables greater flexibility in how the components are applied, structurally and electrically. The fabrication method is multi-layered based on a layer-by-layer construction to achieve a monolithic form. Microelectromechanical Systems (MEMS) approaches based on photolithographic patterning, etching of molds and deposition can be used. Many variations on this approach are possible and depend on whether the components are formed onto macro parts, integrated with or under Integrated Circuits, embedded in circuit boards or packaging, formed separately for pick and place applications, etc.

The inductive components are linear because their inductance varies proportionately with length. Unlike wire-wound inductive coils that occupy an appreciable volume on a circuit board due to their bulkiness, the linear devices of this invention are not required to begin and end at particular locations, are wire-like and can be meandered in the plane to fit into a designed space.

The planar topology of this invention is practical to fabricate, enabling large scale production and low cost.

The inductive components of this invention include inductors, transformers, differential current transformers (DCT), isolation transformers, chokes, filters, mixers, etc.

This invention features an elongated, planar, generally linear electrical inductive component, comprising: at least one conductor, each conductor defining a unique conductive path; a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors; and an insulator separating each conductor from any other conductor and from the magnetic member; wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path.

The component may comprise a single conductor, to accomplish an inductor. The magnetic core may define a magnetic circuit comprising a gap. The conductor may define a gap along its entire length, to create two full-length top and bottom halves, to allow for differential thermal expansion. The insulator may be accomplished in part by a space, to reduce the component capacitance.

The component may comprise two conductors, to accomplish a transformer, or three conductors, to accomplish a differential current transformer. The component may comprise more than two conductors to accomplish a step up or step down transformer with a desired voltage transformation from the input or inputs to the output or outputs.

The magnetic core and all conductors may meander through a plurality of turns, to increase the component's effective length. The meanders may be essentially parallel. The magnetic core may comprise a plurality of laminations separated by non-magnetic insulating material, each lamination completely surrounding all of the conductors.

The component may comprise two or more stacked layers of meanders, to increase the conductor and core length. The component may directly connect between two spaced components in an electrical circuit, to both accomplish a desired inductance as well as carry current between the two spaced components. The invention also features a multiple inductive component inductive circuit comprising a plurality of inductive components of the type described herein,

connected in a desired series and/or parallel circuit combination, to achieve a desired inductance value or voltage conversion.

Also featured is a method of fabricating this component, comprising: fabricating two essentially identical halves, each defining one half of the component; and mechanically and magnetically coupling together the two halves, to create the component.

In another embodiment, the invention features a method of fabricating an elongated, planar, generally linear electrical inductive component by multi-layered fabrication, the component having at least one conductor, each conductor in the component defining a unique conductive path, a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors, and an insulator separating each conductor from any other conductor and all conductors from the magnetic core member, wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, the method comprising: providing a lower layer of magnetic core material; providing on top of the lower layer of magnetic core material, a bottom insulator layer; providing on top of the bottom insulator the at least one conductor; providing an insulator adjacent to the outside and top of each conductor; providing, spaced to the outside of the at least one conductor and the adjacent insulator, vertical segments of the magnetic core, in contact with the lower layer of magnetic core material; and providing over the upper insulator and in contact with the magnetic core vertical segments, an upper magnetic core material, to complete a magnetic core circuit.

Also featured is a method of fabricating an elongated, planar, generally linear electrical inductive component by multi-layered fabrication, the component having at least one conductor, each conductor in the component defining a unique conductive path, a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors,

and an insulator separating each conductor from any other conductor and all conductors from the magnetic core, wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, the method comprising: fabricating two component halves, each half made by: providing a lower layer of magnetic core material; providing on top of the lower layer of magnetic core material, a bottom insulator layer; providing on top of the bottom insulator layer the at least one conductor; providing an insulator adjacent to the outside of each conductor; providing, spaced to the outside of the at least one conductor and the adjacent insulator, vertical segments of the magnetic core, in contact with the lower layer of magnetic core material; and planarizing the top surface of the construction; and then mechanically and magnetically coupling together the planarized surfaces of the two halves, to complete the component.

In another embodiment, the invention features a method of fabricating an elongated, planar, generally linear electrical inductor by multi-layered fabrication, the inductor having a single conductor, a magnetic core co-linear with the conductor along the entire component length, and completely surrounding the conductor, and an insulator separating the conductor from the magnetic core, the method comprising: fabricating two component halves, each half made by: providing a lower layer of magnetic core material; providing spaced vertical segments of the magnetic core, in contact with the lower layer of magnetic core material; providing a bottom insulator layer on top of the lower layer of magnetic core material and the spaced vertical segments; providing the conductor on top of the insulator; and planarizing the top surface of the construction; and then mechanically and magnetically coupling together the planarized surfaces of the two halves, to complete the component.

In yet another embodiment, the invention features a method of fabricating an elongated, planar, generally linear electrical inductor by multi-layered fabrication, the inductor having a single conductor, a magnetic core co-linear

with the conductor along the entire component length, and completely surrounding the conductor, and an insulator separating the conductor from the magnetic core, the method comprising: providing an elongated conductive wire having an essentially circular cross-section; coating the wire with a non-magnetic insulation layer; and coating the insulation layer with a first layer of magnetic core material. This method may further comprise creating a plurality of laminations in the magnetic core by sequentially coating the first layer of magnetic core material with one or more laminations, each comprising a coating of non-magnetic insulating material and then a coating of magnetic core material on top of the coating of non-magnetic insulating material.

In another embodiment, the invention features an elongated, planar, generally linear electrical inductive component, comprising: at least one conductor, each conductor defining a unique conductive path; a magnetic member co-linear with all conductors along the entire component length, and completely surrounding all conductors; and an insulator separating each conductor from any other conductor and from the magnetic member; wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, and the cross section is uniform with length.

The component may comprise a single conductor, to accomplish an inductor, or two co-linear conductors, to accomplish a transformer, or three co-linear conductors, to accomplish a differential current transformer. The magnetic member and all conductors may meander through a plurality of turns, to increase the component's effective length.

Also featured more specifically is an angle measurement instrument for a rotating member having opposed flat faces, comprising: a first pair of capacitive sensors proximate one face of said rotating member; a second pair of capacitive sensors proximate the other face of said rotating member; a planar differential current transformer proximate one pair of capacitive sensors, comprising: two

primary conductors, each comprising a single winding; at least one secondary conductor comprising a single winding; a single magnetic core member surrounding said primary conductors and said secondary conductor; means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor; means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; means for determining from the secondary conductor, the differential currents in the primary conductors, as a measure of the angle of said disk member to said capacitive sensors.

In yet another embodiment, the invention features an angle measurement instrument for determining the angle of a rotating member having opposed faces, relative to fixed members comprising opposing, non-rotating flat faces, comprising: a first pair of capacitive sensor plates fixed to one flat face proximate one face of said rotating member, a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said rotating member, wherein the rotating member rotates to change the gap between the rotating member and the fixed members; a planar differential current transformer comprising: a first conductor comprising one primary carrying current from one set of capacitive sensors; a second conductor comprising a second primary carrying current from a second set of capacitive sensors, the sense of the second current being opposite that of the first current; a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the rotating member; a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length; an insulator separating each conductor from any other conductor and all conductors from the magnetic core; wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length; wherein at any location along the length of

the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length; means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor; means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the angle of said rotating member to said capacitive sensors.

Another embodiment features an angle measurement instrument for determining the angle of a rotating member having opposed faces, relative to fixed members comprising opposing, non-rotating flat faces, comprising: a first pair of capacitive sensor plates fixed to one flat face proximate one face of said rotating member, a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said rotating member, a planar differential current transformer comprising: a first conductor comprising one primary carrying current from one set of capacitive sensors; a second conductor comprising a second primary carrying current from a second set of capacitive sensors, the sense of the second current being opposite that of the first current; a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the rotating member; a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length; an insulator separating each conductor from any other conductor and all conductors from the magnetic core; wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length; wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length; means for electrically connecting

one capacitive sensor from each pair in parallel to one primary conductor; means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the angle of said rotating member to said capacitive sensors.

Also featured is a translation measurement instrument for determining movement of a moving member having opposed faces, relative to fixed members comprising two opposing, fixed flat faces, comprising: a first pair of capacitive sensor plates fixed to one flat face proximate one face of said moving member, a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said moving member; wherein the moving member moves to vary the gap between the moving member and the fixed members; a planar differential current transformer comprising: a first conductor comprising one primary carrying current from one set of capacitive sensors; a second conductor comprising a second primary carrying current from a second set of capacitive sensors, wherein the sense of the second current is opposite that of the first current; a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the moving member; a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length; an insulator separating each conductor from any other conductor and all conductors from the magnetic core; wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length; wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length; means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor; means for electrically connecting the other capacitive sensor

from each pair in parallel to the other primary conductor; and means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the translation distance of said moving member to said capacitive sensors.

Also included is a translation measurement instrument for determining movement of a moving member having opposed faces, relative to fixed members comprising opposing, fixed flat faces, comprising: a first pair of capacitive sensor plates fixed to one flat face proximate one face of said moving member, a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said moving member, wherein the moving member moves relative to the fixed members; a planar differential current transformer comprising: a first conductor comprising one primary carrying current from one set of capacitive sensors; a second conductor comprising a second primary carrying current from a second set of capacitive sensors, wherein the sense of the second current is opposite that of the first current; a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the translating member; a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length; an insulator separating each conductor from any other conductor and all conductors from the magnetic core; wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length; wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length; means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor; means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and means for determining from the third conductor, the differential currents in

the primary conductors, as a measure of the translation distance of said moving member to said capacitive sensors.

Another embodiment features a method of fabricating an elongated, planar, generally linear electrical inductive component by multi-layered fabrication, the component having at least one conductor, each conductor in the component defining a unique conductive path, a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors, and an insulator separating each conductor from any other conductor and all conductors from the magnetic core member, wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, and the cross section is uniform with length, the method comprising: providing a lower layer of magnetic core material; layering on top of the lower layer of magnetic core material, a second layer comprising a bottom insulator and first vertical segments of the magnetic core; wherein the first vertical segments of the magnetic core are in contact with the lower layer of magnetic core material; layering on top of the second layer, a third layer comprising conductors and insulators, bounded on each side in the plane by second vertical segments of the magnetic core, the conductors separated from each other and from the second magnetic core vertical segments by a vertical insulator segment; wherein the second vertical segments of the magnetic core are located directly above and in contact with the first vertical segments of the magnetic core of the second layer; layering on top of the third layer, a fourth layer comprising a top insulator and third vertical segments of the magnetic core, the third vertical segments of the magnetic core located directly above and in contact with the second vertical segments of the magnetic core; layering on top of the fourth layer, a fifth layer comprising a top layer of magnetic core material that is in contact with the third vertical segments of the magnetic core.

In this embodiment, the component may comprise one conductor to accomplish an inductor, or two co-linear conductors, each conductor defining a unique path, to accomplish a transformer, or three co-linear conductors, each conductor defining a unique path, to accomplish a differential current transformer, wherein one conductor comprises one primary, the second conductor comprises a second primary and the third conductor comprises the secondary. The method of fabrication may be by sequential deposition. The deposition may comprise in part electroplating. The method of fabrication may be by stacking and bonding of multiple layers formed separately.

Brief Description of the Drawings

Other objects, features and advantages will occur to those skilled in the art from the following descriptions of the preferred embodiments, and the accompanying drawings, in which:

Figure 1 is a schematic representation of a rotating member placed between a differential arrangement of parallel capacitor plates (a capacitive transducer).

Figure 2 is an exploded view of a planar, toroidal transformer fabricated using photolithographic patterning, etching and additive processes.

Figure 3 is a schematic illustration of the DCT invention.

Figure 4 is a view of a conceptual cross-section of the DCT having unit length.

Figure 5 is a view of a conceptual cross-section of the DCT of unit length with magnetic laminations included to reduce eddy currents.

Figure 6 is a view of a conceptual cross-section of a one-to-one ratio transformer of unit length.

Figure 7 is a view of a conceptual cross-section of an inductor of unit length.

Figure 8 is a view of a conceptual cross-section of an inductor with magnetic laminations included to reduce eddy currents.

Figure 9 is an electrical circuit model for an inductor having a gap in the core.

Figure 10 is a view of a conceptual cross-section of an inductor with a gap in the magnetic core.

Figure 11 is a conceptual rendition of a DCT transformer meandered to form a planar rectangular arrangement.

Figure 12 is a view of a stack of connected layers, each layer of which is a transformer meandered to form a planar rectangular shape. The layers may be serially connected to achieve the proper transformer length.

Figure 13 is a conceptual rendition of a parallel/series connection of similar inductors to form a second inductance value.

Figure 14 is a conceptual rendition of two one-to-one voltage ratio transformers connected to form a two-to-one ratio step-down transformer by means of connecting the secondaries in parallel and connecting the primaries in series.

Figure 15 is a conceptual rendition of connected primaries and secondaries of four one-to-one ratio identical transformers to form a step-down transformer of five-to-two voltage ratio.

Figure 16 demonstrates the utility of linear inductive components of this invention in an example circuit board in which the component can take the form of a connecting wire with inductance, as an inductive component imbedded within the board and as an inductive component structure formed on the surface of the board itself.

Figure 17a is a view of a conceptual cross-section of a DCT formed by using sandwich construction.

Figure 17b is a view of a conceptual cross-section of a transformer having six conductors and formed by sandwich construction.

Figure 18a is a view of a conceptual cross-section of an inductor formed by sandwich construction.

Figure 18b is a view of a conceptual cross-section of an inductor with symmetric gaps in the magnetic core formed by sandwich construction.

Figure 18c is a view of a conceptual cross-section of an inductor with gaps in the core and air spaces in the insulator region.

Figure 18d is a view of a conceptual cross-section of an inductor with an air gap for thermal expansion. The conductors are connected externally.

Figure 19 is a conceptual rendition of a power splitter concept formed using sandwich construction wherein the primary is a single larger conductor and three separate, smaller conductors are secondaries; the conductor sizes are selected to match the resistive losses of the four conductors.

Figure 20 is the view of a conceptual cross-section of an inductor of circular geometry having the conductor, insulator and magnetic core arranged coaxially.

Figure 21a is a circuit diagram of the capacitive pick-off.

Figure 21b is a circuit diagram of the capacitive pick-off with the planar DCT included.

Figure 22a depicts successive steps of a first process for the fabrication of a DCT or other inductive components.

Figure 22b depicts additional steps of a first process for the fabrication of a DCT or other inductive components.

Figure 22c depicts additional steps of a first process for the fabrication of a DCT or other inductive components.

Figures 23a - f depict successive steps of a second process for the fabrication of a DCT or other inductive component.

Figure 24a - e depict successive steps of a third process for the fabrication of an inductor formed using sandwich construction.

Description of the Preferred Embodiments of the Invention

This invention eliminates the need to form conductor coil windings about a magnetic core in the fabrication of inductive components. Instead, the magnetic core is formed about the conductor, or a set of conductors, encircling them along the full component length. The conductors are separated from each other and the magnetic core by electrically insulating material. The topology can be wire-like having a cross-section that is essentially uniform along the device length and the desired inductance is achieved by varying the length. The conductors, insulators and magnetic core are collinear. For each application, the design process determines the cross-section dimensions and the materials, which will determine the Q. The thinness of the component results from the cross section dimensions.

The concept can be understood by referring to Figure 3 which depicts a three conductor DCT. Two conductors form the primary windings (albeit straight) 18, 20 and the single secondary winding 22. All three conductors pass through circular magnetic cores 24.

Planar Inductive Components

Differential Current Transformer

Figure 4 describes the cross-sectional view of a differential current transformer (DCT) 26 having unit length. It includes three conductors: two for the primary circuit 28, 30 and one for the secondary 32. The conductors are separated by electrically-insulating material 34 and the conductors and insulators are surrounded by a magnetic core 36, made of suitable material.

The relevant dimensions are: the magnetic circuit length, s, the thickness of the magnetic core, t_c, the conductor width and height, both 3a in this case, and the separation between conductors, a in this case.

The relevant material properties are the conductor resistivity, ρ_C, and the magnetic material permeability, $\mu_r \mu_o$.

The frequency of operation is also important because it limits the effective thickness of the magnetic core to twice the skin depth as a result of eddy currents.

The values of the geometric parameters of the device cross-section will depend on the material properties and achievable fabrication tolerances in fabricating the different features of the device.

Analytically the inductance and Q of the device may be derived as follows. The device described by Figure 4 consists of a symmetric, closed magnetic circuit of length s (dotted line). From Ampere's Law, the line integral of the magnetic field, H, along the encircling core is equal to the current, i, that it encloses.

$$\oint \overline{H} \cdot d\overline{s} = Hs = i \tag{1}$$

The magnetic flux density, B, is related to H by $B = \mu_r \mu_o H$ where μ_r is the relative permeability and μ_o the permeability of free space. The flux in the magnetic circuit is then given by the integral of the flux density

$$\Phi = \int_A \overline{B} \cdot d\overline{A} = BA = Bt_c l_c \tag{2}$$

where $A = t_c l_c$ is the cross-sectional area which the flux crosses.

The inductance is given by the ratio of the flux linking the conductor to the current, i. Since the flux linkage for this design is equal to the flux, Φ, the inductance is given by

$$L = \frac{\Phi}{i} \tag{3}$$

Using the results of the above expressions, the inductance can be written as

$$L = \frac{\Phi}{i} = \mu_r \mu_o \frac{t_c l_c}{s} \qquad (4)$$

in terms of geometric parameters and material properties.

The quality factor, Q, for an inductor without core losses is given by

$$Q = \frac{L\omega}{R_s + R_A} \qquad (5)$$

where R_s and R_a are the transformer conductor and secondary load resistances, respectively and ω is the angular frequency of the excitation.

An interesting and convenient result for the Q is obtained when the quality factor expression is rewritten in terms of geometric parameters, assuming a negligible secondary load resistance, R_a. The Q becomes

$$Q \cong \frac{9\mu_r \mu_o t_c a^2 \omega}{s\rho_c} \qquad (6)$$

where the transformer resistance, R_s, is replaced by the expression

$$R_s = \frac{\rho_c l_c}{9a^2} \qquad (7)$$

The Q is seen to be independent of length, therefore the resistance and the inductance can be determined per unit length and the only relevant geometric parameters are those of the cell cross-section.

The formulas above assume that the thickness of the magnetic core are less than the skin depth δ, the depth of penetration of the magnetic field in the core or $N\delta$ in the case where laminations are used to ensure that the magnetic flux, ϕ , fully penetrates the core.

The skin depth δ is given by

$$\delta = \sqrt{\frac{2\rho_m}{\mu_r \mu_0 \omega}} \tag{8}$$

where

μ_r = relative permeability

μ_0 = permeability of free space ($4\pi \times 10^{-7}$ Henries/meter)

ρ_m = resistivity of the magnetic material

ρ_c = conductor resistivity (copper 1.72×10^{-8} ohm/meter)

$\omega = 2\pi f$ (where f is the frequency of applied fields)

Figure 5 shows a differential current transformer 38 constructed with magnetic laminations 40 to reduce the effects of eddy currents, which were ignored in the preceding development. A non-magnetic, insulating material 42 separates individual laminations.

From equation 6, Q can be maximized by:

a. increasing the magnetic core thickness, t_c , and hence core cross sectional area,
b. reducing the magnetic circuit length, s, but that depends on the conductor dimensions,
c. increasing the conductor cross section and hence reducing the conductor resistance, R_s ,
d. increasing the core permeability, μ_r and

e. reducing the conductor resistivity, ρ_C.

Other design considerations include:

a. saturation of the core,

b. choice of electrical insulation material and spacing between inductors,

c. choice of non-magnetic material for forming laminations,

d. the capacitance between the conductors and between the conductors and the core which will define the self resonant frequency of the transformer or inductor,

e. choice of core material and permeability,

f. effects of stress on the inductive properties,

g. effects of temperature on the inductive properties,

h. lowest resistivity for the conductor material,

i. uninterrupted magnetic circuit unless desired as in the case of gaps,

j. impedance matching between windings in transformer designs

The benefits of this invention include:

a. Ability to use low aspect ratio fabrication technology.

b. The conductors are continuous in the plane of the device; connections between conductors at different levels are not required.

c. Small magnetic material thicknesses may be used, which are within current fabrication capability.

d. Excellent matching for coupling between primaries and a common secondary is a natural result of the invention.

e. The magnetic field is contained within the magnetic core eliminating external flux leakage.

f. Coupling between conductors is unity by geometry.

g. The inductance of the DCT, inductors and other transformers of this invention can be determined per unit length; the total inductance is then determined by the total length, while the Q is independent of length.

h. The design is linear and is not restricted to a particular geometry and can in fact meander to fit in available spaces on the substrate.

One-to-one ratio transformer

A one-to-one ratio transformer 43 is shown in Figure 6. It includes a single primary conductor 44 and a single secondary conductor 46. An insulator 48 separates the conductors from each other and the core. A magnetic material 50 encircles the insulator and conductors. Based on the dimensions shown in Figure 6, the inductance, series resistance and capacitance between conductors are given by

$$L = \frac{\mu_r \mu_o t_c l_c}{28a + \pi t_c} \tag{9}$$

$$R = \frac{\rho l_c}{9a^2} \tag{10}$$

$$C_{\mu s} = \varepsilon_r \varepsilon_o l_c \tag{11}$$

Inductor

An inductor configuration 52 is shown in Figure 7. It consists of a single conductor 54 enclosed by an insulator 56. Both the conductor and insulator are encircled by the magnetic core 58. For this configuration, the calculations for the inductance, series resistance, and capacitance are

$$L = \frac{\mu_r \mu_o t_c l_c}{20a + \pi t_c} \tag{12}$$

$$R = \frac{\rho l_c}{9a^2} \tag{13}$$

$$C = 12 \varepsilon_r \varepsilon_o l_c \tag{14}$$

Figure 8 shows an inductor configuration 60 with 4 magnetic laminations 62. The laminations are separated by a non-magnetic, insulating material 64.

Inductor with losses and core gap

A more complete description of the inductor includes the effects of hysteresis and eddy current losses as well as the use of a gap in the magnetic circuit. An equivalent circuit 66 is shown in Figure 9. It applies to the inductor configuration 67 shown in Figure 10. A gap 68 is located in the magnetic circuit and extends the full length of the inductor in this case.

The conductor resistance, R_s, depends on the conductor resistivity, ρ_c, cross-sectional area, A_c and inductor length, l_c, as given by

$$R_s = \frac{\rho_c l_c}{A_c} \tag{15}$$

The equivalent resistance contributed by eddy current losses depends on the path length, s, of the magnetic field in the core, the laminated core thickness, t_c, the magnetic core resistivity, ρ_m, and the number of laminations, N, is given as

$$R_e = \frac{12\rho_c l_c}{t_c s} \cdot (N+1)^2 \tag{16}$$

The equivalent resistance contributed by hysteresis losses is given by

$$R_h = \frac{kL\omega}{2\pi(1+\mu_r g/s)} \tag{17}$$

where $L = \frac{\mu_r \mu_o t_c l_c}{s + \mu_r g}$ is the inductance, $\omega = 2\pi f$ is the angular frequency for an excitation frequency of f, and g is the inductor gap. μ_o is the permeability in air and μ_r is the relative permeability of the magnetic material. k is a factor much less than one typically, which is dependent on the shape of the hysteresis loop. The inductance for the lossless inductor is given by $j\omega L$.

The quality factor, Q, is given by

$$Q = \frac{L\omega}{R_s\left(\frac{R_e + R_h}{R_e}\right) + R_h\left(1 + \frac{R_h}{R_e}\right) + \frac{(L\omega)^2}{R_e}} \tag{18}$$

For the inductor case it is desirable for these conditions to be met: $R_e >> L\omega$ and $R_h << R_e$. The form for Q then reduces to

$$Q = \frac{L\omega}{R_s + R_h + \frac{L\omega}{R_e} \cdot L\omega} \tag{19}$$

From this form it can be seen that for low frequencies the Q dependence goes as $Q = \frac{L\omega}{R_s + R_h}$ whereas for high frequencies Q tends to values less than one. It is therefore important to laminate as much as possible to keep $R_e >> L\omega$ at the frequency of interest. The use of the gap also is useful in that it reduces the equivalent hysteresis loss.

Meandering Form

To achieve the desired inductance, the inductive component must have the proper length. A top view of the DCT 70 is shown in Figure 11 for a

rectangular device shape. The conductors and core are shown to meander 72 back and forth from side to side to achieve the necessary total length. The thin side cross-section 74 is shown. The external connections to the DCT can be made at the pads 76, 77, 78. In the meander detail shown in the enlarged view 79 are indicated a first primary 80, a second primary 81 and the secondary 82. The DCT is not limited to the rectangular shape shown, however, and can in fact meander along arbitrary paths and form any shape according to available space in the application. An electrical insulator 83 separates the conductors from each other and the conductors from the magnetic core 84.

Stack Construction

In the case where the available surface area is not sufficiently large to allow the required conductor and core length to be formed, additional inductance can be obtained by repeating layers to form a stack 86; three levels 87 connected in series are shown in Figure 12 for this DCT 88 example.

Uses of Inductive Building Blocks

It may happen that fabrication and cost considerations will drive the inductive component designs to standard size products with specified inductance values. These can then be connected to obtain inductance values required. Figure 13 is an example of two inductors 90, 91 connected in parallel which are in turn connected in series with inductor 92 to yield an inductance value of 1.5 times that of an individual inductor. Figure 14 is an example of a 2-to-1 step-down voltage transformer 94 which is formed by connecting in parallel the secondaries 95, 96 of two identical one-to-one ratio transformers 97, 98 and connecting in series the primaries 99, 100 of the same transformers. The output is connected to a load 89. Figure 15 is a step-down voltage transformer 93 in the ratio of five to two. It includes four identical one-to-one ratio transformers 102, 105, 106, 107 with primaries and secondaries connected in the proper

series/parallel combination. The output is attached to a load 142. Other step-up and step-down variations will occur to those skilled in the art.

Implementation of a linear inductive component

Because the inductive component is linear (wire-like), it offers flexibility in how it can be implemented in applications. Figure 16 shows three examples carried out on a printed circuit board 108. The first example shows the inductive component 109 imbedded in the board. The second example shows the inductive component as an inductive wire 110 connecting two other components (it is an inductor as well as a connecting conductor). In addition, in the second example, the wire is fully shielded to reduce leakage (coupling with other circuits). In the third example, the inductive component is formed as a meandered planar component 114 to occupy a space on the board over which another component 115 can be located.

Inductive components can also be fabricated onto macro parts where the proximity provides an advantage. In sensor applications, the differential current transformer differences the signals prior to transmission to supporting electronics and therefore minimizes signal degradation by pick-up from external sources.

Sandwich Construction

Inductive components such as the DCT 120 shown in Figure 17a may be fabricated in two independently fabricated halves, a top half 122 and a bottom half 123, which are then joined. This method of construction may be preferred for some methods of fabrication. Note that the conductors 124 come into direct contact and the laminated magnetic cores 125 also come into direct contact. Another variation on the transformer design 126 separates the conductors 127 with an electrical insulator layer 128 while retaining intimate contact between the magnetic cores 129 as shown in Figure 17b. The insulating layer can be an air

space, thereby allowing thermal expansion of the conductor without stressing the component.

Figure 18a depicts an inductor 130 formed by the sandwich method. Note that the conductors 131 come into direct contact and the laminated magnetic cores 132 come into direct contact. Figure 18b depicts the inductor 134 with symmetric non-magnetic, insulating gaps 133 in the magnetic core. The gap is formed with a non-magnetic, insulating material. The sandwich configuration is very convenient for the construction of a gap in the core. Figure 18c depicts a inductor 136 with a gap which also utilizes an air space 137 to decrease the capacitance between the conductor and the magnetic core.

Figure 18d depicts an inductor 143 which is a variation on the inductor cross-section design of Figure 18c. By fabricating the two halves so that the conductor does not come into contact, via an expansion space 135 , the differential thermal expansion between the insulator 103 and magnetic core 121 will not produce stress on the component.

The sandwich construction also makes possible an alternate transformer 138 with cross-section geometries as shown in Figure 19 in which the top 139 and bottom 140 halves have different conductor arrangements. In this case three secondaries 141 are situated in the lower half and a single much wider primary 142 is situated in the top half. This particular form is optimum for a power splitter in which the resistive losses are matched in each conductor.

A DCT having a larger secondary in the top half and the two smaller primaries in the lower half would also match the resistive power losses for that configuration. Other cross-section designs will occur to those skilled in the art.

Circular cross section configuration

Although the cross-sections of the inductive components of the invention have been depicted as essentially rectangular, other cross-section shapes are possible, such as elliptical or round. Figure 20 depicts an inductor with round

cross section 152. A circular conductor 153 is coated with insulation 154 and subsequently coated with a magnetic core material 155 in a coaxial arrangement. A two lamination configuration is shown with non-magnetic insulating layer 156 between the two laminations.

Other useful cross-section shapes will occur to those skilled in the art.

Capacitive Pick-off Application with DCT

Figure 21a illustrates the full tilt pick-off which includes the capacitive plates 212, the Differential Current Transformer (DCT) 213 and current to voltage electronics 214. Figure 21b illustrates the full tilt pick-off which includes the capacitive plates 215, the planar DCT 216 and current to voltage electronics 217.

In the DCT, two currents flow to a common tap to ground. When the capacitive transducer is tilted, one of the currents becomes greater than the other and a current is induced in the secondary. The resultant current is converted to a voltage using an operational amplifier.

It is desired to locate the differential current transformer (DCT) next to the capacitive plates in order to take the current difference at the signal source and amplify it before capacitive noise pick-up in the leads can become a problem.

For miniature, essentially planar devices which are fabricated with an assembly of planar layers, it is desirable for the DCT to also have a planar form so that it can either be formed or be placed next to the transducer. At this time custom-wound ferrite cores are used. Their shape and size make it difficult to place it sufficiently close to the transducer. In addition, the core winding leads are susceptible to pick-up themselves.

The planar transformer approach will allow inductive components to be fabricated directly onto parts in many applications. The prospect of integration with IC chips and package structures may replace the current approach of pick and placement of wound cores onto parts, and would result in a much more cost effective approach.

In addition to angular detection, translations can also be measured with a suitable differential configuration of capacitive plates.

Saturation is a minor consideration since the currents are expected to be very small in the DCT for two reasons : (1) the pick-off differences the currents in the primaries yielding zero current at zero rotation of the tilting member and (2) gyros and accelerometers are to be operated in closed-loop mode (rotation at null). The core thickness is primarily set by the inductance requirement and not saturation.

First Fabrication Process Description

A fabrication process for the millimachined differential current transformer (MilliDCT) is based on the successive application of patterning by photolithography and through-mold electroforming.

A fabrication sequence for the differential current transformer is given below and illustrated in Figure 22. Other variations are possible.

Step 1. Two choices of substrate are possible: either a highly permeable material 285 (e.g., a supermalloy wafer or sheet); or a substrate 286 onto which supermalloy can be deposited to form the lower magnetic core.

Step 2. The lower magnetic core is coated with a thin (5 microns) layer of insulating material, such as polyimide, followed by a sputtered seed layer of copper. Photoresist is then applied and exposed with Mask 1 287. The resulting pattern allows a deposition of a 'mesh-type' seed layer on the insulating film 288 for the deposition of conductor lines (electrodeposition is preferred over electroless deposition here due to the improved electrical properties of electrodeposited films). The connector mesh lines 289 connect the separate devices and test structures on the wafer.

Step 3. A thick layer of high-aspect-ratio photodefinable material, such as SU-8-based epoxy, is then deposited and patterned with Mask 2 290, to form the conductor molds 291 and necessary molds 291 for the magnetic side cores.

Step 4. The conductors 292 are electroformed into the plating molds, (note at this point the electrical contact for the magnetic side cores are covered with the first insulating material; thus, no electrodeposition occurs in these molds). The insulating polyimide 293 at the bottom of the magnetic side core molds is then selectively removed using a reactive ion etch in preparation for deposition.

Step 5. The magnetic side cores 294 are now electroplated using either permalloy or supermalloy. The entire structure is then passivated using an insulating material 295 such as preimidized polyimide, over which a magnetic seed layer is then sputter deposited.

Step 6. Photoresist is then applied to the magnetic seed layer, patterned and etched using Mask 3 296 to expose the preimidized polyimide. The seed layer is now used as the mask to open the preimidized polyimide using a plasma etch to allow access to the magnetic side cores. This allows the formation of magnetic vias 297 between the magnetic side core and the magnetic upper core with deposited supermalloy.

Step 7. A polymeric plating mold is then deposited and patterned, and the upper magnetic core of supermalloy is deposited in a two step process. First the lower magnetic core is connected to a voltage source, and the magnetic upper side core 299 is deposited. Next the magnetic upper seed layer is connected to a voltage source, and the magnetic upper core 300 is deposited to complete the uniting of the upper and lower magnetic cores of the transformer.

Step 8. The polymeric plating mold is removed, and the seed layer beneath the polymeric plating mold is etched, separating the magnetic core and completing the magnetic circuit.

Step 9. To complete the device, the wafer is blanket etched in an oxidizing plasma to remove the polymers in the fields 305 (the magnetic core itself will shield the polymer internal to the device during this etch; the exposed conductor lines where the pads are will shield the polymer underneath them thus remaining supported by that polymer). Finally, to complete the device, the mesh-connector lines which are exposed during the blanket etch, are etched to electrically isolate the conductor lines of the different devices and test structures.

Silicon wafers are an obvious choice for the substrate since they have a polished, flat surface, mechanical stability, and compatibility with Silicon-based gyros and accelerometers being developed by Millimachining and MEMS. In addition, the separate components can be easily diced.

The component fabrication is not restricted to Silicon, however, and the prospect of forming the component directly onto parts made of other materials may be desirable for some applications.

Second Fabrication Process Description

Figures 23a through 23f describe a process currently in use for fabricating the DCT. It can also be applied to a transformer (two conductors) and an inductor (one conductor). The non-laminated core approach will be described in the following series of steps.

Step a. A thin film of copper 160 is sputter deposited onto a substrate 161 with the proper flatness and polish. The substrate should be a good thermal conductor. Copper is used as a sacrificial layer, which can be removed at the end of the entire process allowing the separation of the component from the substrate. A layer of magnetic material 162 is then electroplated onto the copper

layer forming the bottom half of the magnetic core. The substrate can be silicon for IC integration.

Step b. A sputtered film of titanium 164 or chromium metal is applied to the magnetic material to enhance adhesion for the following insulator material. The insulator layer 165 is then applied and patterned to allow access 166 for the magnetic core sidewalls. Onto the insulator material is then sputtered a thin layer of titanium/copper/titanium 167 which is patterned to provide seed footings in preparation for conductor plating in a later step. Lastly, a resist 168 having the thickness of the conductor is applied.

Step c. The thick resist is patterned and developed to form deep molds 170 down to the conductor footings. After the resist is developed, the exposed titanium is stripped and the conductor material (copper) 171 is plated into the mold followed by planarization of the surface. The thick resist 172 is then stripped

Step d. The thick resist is stripped leaving the formed conductors 174 and opening access 175 to the titanium on the surface of the lower magnetic core. The titanium layer is then etched away.

Step e. A layer of resist 176 is applied to the thickness required for the magnetic core sidewalls. The resist above and between the conductors will serve as the insulator material 177 since the resist in non-conductive electrically. The resist is then patterned and developed to form molds 178 followed by electroplating into the molds by a magnetic material 179 such as Permalloy. A planarization step follows.

Step f. A magnetic thin film 180 is applied to the top surface connecting the sidewalls 181 and covering the insulator material 182. More plating 184 is done on top of the thin layer to form the top segment of the core.

Conformal formation of magnetic core

Conformal plating is an alternate approach to the formation of the sidewalls and top surface of the magnetic core. Continuing from step e, prior to electroplating into the core sidewall molds, a thin seed layer is applied into the molds and over the insulator material. Electroplating is then carried out to form a conformal magnetic core into the sidewalls and over the insulator. The advantage to conformal construction is that alternating thicknesses of magnetic and non-magnetic materials can be applied to form magnetic laminations.

Third Fabrication Process Description

This process describes the fabrication of an inductor using one mask. Figures 24a through 24e describe the process steps.

Step a. A suitable substrate 186 is selected onto which a thin film of copper 187 is deposited. Copper serves as the sacrificial layer which will allow the separation of the component from the substrate. A magnetic material 188 is then deposited onto the copper film to form the bottom segment of the core.

Step b. A Titanium layer 190 is sputter deposited onto the copper layer for adhesion of the resist. 80 microns of resist 191 is then applied. Photo mask one (not shown) is then used to create molds 192 for the core sidewalls 193. The titanium is then etched away from the bottom of the molds to access the magnetic layer which is also plasma cleaned. A magnetic material such as Permalloy is deposited into the molds and planarized.

Step c. The resist is stripped and a conformal coat of insulator 196 such as parylene is applied to the exposed structures.

Step d. A titanium seed layer 198 is sputtered onto the structure. A conformal coating of conductor material 199 such as copper is plated over the structure as shown.

Step e. Planarization is done to bring the copper and magnetic material sidewalls to the same height.

Step f. Two halves are joined and bonded to form a sandwich construction. (Not shown)

This approach forms one half of the sandwich construction approach. After the second half is made the two are aligned using reference devices such as pins and joined. An advantage of this process is that it uses a thinner resist than in the first process described above and thereby greatly reducing the process time and cost.

General Fabrication Procedure

Other fabrication procedures will occur to those skilled in the art.

Although specific features of the invention are shown in some drawings and not others, this is not a limitation of the invention. Other embodiments will occur to those skilled in the art, and are within the scope of the following claims.

What is claimed is:

1. An elongated, planar, generally linear electrical inductive component, comprising:

at least one conductor, each conductor defining a unique conductive path;

a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors; and

an insulator separating each conductor from any other conductor and from the magnetic member;

wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path.

2. The component of claim 1 comprising a single conductor, to accomplish an inductor.

3. The component of claim 2, wherein the magnetic core defines a magnetic circuit comprising a gap.

4. The component of claim 2, wherein the conductor defines a gap along its entire length, to create two full-length top and bottom halves, to allow for differential thermal expansion.

5. The component of claim 2 wherein the insulator is in part accomplished by a space, to reduce the component capacitance.

6. The component of claim 1 comprising two conductors, to accomplish a transformer.

7. The component of claim 1 comprising three conductors, to accomplish a differential current transformer.

8. The component of claim 1 comprising more than two conductors to accomplish a step up or step down transformer with a desired voltage transformation from the input or inputs to the output or outputs.

9. The component of claim 1 wherein the magnetic core and all conductors meander through a plurality of turns, to increase the component's effective length.

10. The component of claim 9 wherein the meanders are essentially parallel.

11. The component of claim 1, wherein the magnetic core comprises a plurality of laminations separated by non-magnetic insulating material, each lamination completely surrounding all of the conductors.

12. The component of claim 1, wherein at least one conductor defines a gap along its entire length, to define two full-length top and bottom halves, to allow for differential thermal expansion.

13. A method of fabricating the component of claim 1, comprising:

fabricating two essentially identical halves, each defining one half of the component; and

mechanically and magnetically coupling together the two halves, to create the component.

14. A method of fabricating an elongated, planar, generally linear electrical inductive component by multi-layered fabrication, the component having at least one conductor, each conductor in the component defining a unique conductive path, a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors, and an insulator separating each conductor from any other conductor and all conductors from the magnetic core member, wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, the method comprising:

providing a lower layer of magnetic core material;

providing on top of the lower layer of magnetic core material, a bottom insulator layer;

providing on top of the bottom insulator the at least one conductor;

providing an insulator adjacent to the outside and top of each conductor;

providing, spaced to the outside of the at least one conductor and the adjacent insulator, vertical segments of the magnetic core, in contact with the lower layer of magnetic core material; and

providing over the upper insulator and in contact with the magnetic core vertical segments, an upper magnetic core material, to complete a magnetic core circuit.

15. The method of claim 14 wherein the component comprises a single conductor, to accomplish an inductor.

16. The method of claim 15, wherein the magnetic core defines a circuit comprising a gap.

17. The method of claim 15, wherein the conductor defines a gap along its entire length, to define two full-length top and bottom halves, to allow for differential thermal expansion.

18. The method of claim 15 wherein the insulator is in part accomplished by a space, to reduce the component capacitance.

19. The method of claim 14 comprising two conductors, to accomplish a transformer.

20. The method of claim 14 comprising three conductors, to accomplish a differential current transformer.

21. The method of claim 14 comprising more than two conductors to accomplish a step up or step down transformer with a desired voltage transformation from the input or inputs to the output or outputs.

22. The method of claim 14 wherein the magnetic core and all conductors meander through a plurality of turns, to increase the component's effective length.

23. The method of claim 14, wherein the magnetic core comprises a plurality of laminations separated by non-magnetic insulating material, each lamination completely surrounding all of the conductors.

24. The method of claim 14, wherein at least one conductor defines a gap along its entire length, to create two full-length top and bottom halves, to allow for differential thermal expansion.

25. A method of fabricating an elongated, planar, generally linear electrical inductive component by multi-layered fabrication, the component having at least one conductor, each conductor in the component defining a unique conductive path, a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors, and an insulator separating each conductor from any other conductor and all conductors from the magnetic core, wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, the method comprising:

a. fabricating two component halves, each half made by:

providing a lower layer of magnetic core material;

providing on top of the lower layer of magnetic core material, a bottom insulator layer;

providing on top of the bottom insulator layer the at least one conductor;

providing an insulator adjacent to the outside of each conductor;

providing, spaced to the outside of the at least one conductor and the adjacent insulator, vertical segments of the magnetic core, in contact with the lower layer of magnetic core material; and

planarizing the top surface of the construction; and

b. mechanically and magnetically coupling together the planarized surfaces of the two halves, to complete the component.

26. The method of claim 25 wherein the component comprises a single conductor, to accomplish an inductor.

27. The method of claim 26, wherein the magnetic core defines a magnetic circuit comprising a gap.

28. The method of claim 26, wherein the conductor defines a gap along its entire length, to create two full-length top and bottom halves, to allow for differential thermal expansion.

29. The method of claim 26 wherein the insulator is in part accomplished by a space, to reduce the component capacitance.

30. The method of claim 25 comprising two conductors, to accomplish a transformer.

31. The method of claim 25 comprising three conductors, to accomplish a differential current transformer.

32. The method of claim 25 comprising more than two conductors to accomplish a step up or step down transformer with a desired voltage transformation from the input or inputs to the output or outputs.

33. The method of claim 25 wherein the magnetic core and all conductors meander through a plurality of turns, to increase the component's effective length.

34. The method of claim 25, wherein the magnetic core comprises a plurality of laminations separated by non-magnetic insulating material, each lamination completely surrounding all of the conductors.

35. The method of claim 25, wherein at least one conductor defines a gap along its entire length, to define two full-length top and bottom halves, to allow for differential thermal expansion.

36. A method of fabricating an elongated, planar, generally linear electrical inductor by multi-layered fabrication, the inductor having a single conductor, a magnetic core co-linear with the conductor along the entire component length, and completely surrounding the conductor, and an insulator separating the conductor from the magnetic core, the method comprising:

a. fabricating two component halves, each half made by:

providing a lower layer of magnetic core material;

providing spaced vertical segments of the magnetic core, in contact with the lower layer of magnetic core material;

providing a bottom insulator layer on top of the lower layer of magnetic core material and the spaced vertical segments;

providing the conductor on top of the insulator; and

planarizing the top surface of the construction; and

b. mechanically and magnetically coupling together the planarized surfaces of the two halves, to complete the component.

37. The method of claim 36, wherein the magnetic core defines a magnetic circuit comprising a gap.

38. The method of claim 36, wherein the conductor defines a gap along its entire length, to create two full-length top and bottom halves, to allow for differential thermal expansion.

39. The method of claim 36 wherein the insulator is in part accomplished by a space, to reduce the component capacitance.

40. The method of claim 36 wherein the magnetic circuit and all conductors meander through a plurality of turns, to increase the component's effective length.

41. The method of claim 40, wherein the magnetic circuit comprises a plurality of laminations separated by non-magnetic insulating material, each lamination completely surrounding all of the conductors.

42. The method of claim 36, wherein the conductor defines a gap along its entire length, to define two full-length top and bottom halves, to allow for differential thermal expansion.

43. A method of fabricating an elongated, planar, generally linear electrical inductor by multi-layered fabrication, the inductor having a single conductor, a magnetic core co-linear with the conductor along the entire component length, and completely surrounding the conductor, and an insulator separating the conductor from the magnetic core, the method comprising:

providing an elongated conductive wire having an essentially circular cross-section;

coating the wire with a non-magnetic insulation layer; and

coating the non-magnetic insulation layer with a first layer of magnetic core material.

44. The method of claim 43, further comprising creating a plurality of laminations in the magnetic core by sequentially coating the first layer of magnetic core material with one or more laminations, each comprising a coating of non-magnetic insulating material and then a coating of magnetic core material on top of the coating of non-magnetic insulating material.

45. The component of claim 9, wherein the component comprises two or more stacked layers of meanders, to increase the conductor and core length.

46. The component of claim 1, wherein the component directly connects between two spaced components in an electrical circuit, to both accomplish a desired inductance as well as carry current between the two spaced components.

47. A multiple inductive component inductive circuit comprising a plurality of inductive components of claim 1 connected in a desired series and/or parallel circuit combination, to achieve a desired inductance value or voltage conversion.

48. An elongated, planar, generally linear electrical inductive component, comprising:

at least one conductor, each conductor defining a unique conductive path;

a magnetic member co-linear with all conductors along the entire component length, and completely surrounding all conductors; and

an insulator separating each conductor from any other conductor and from the magnetic member;

wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, and the cross section is uniform with length.

49. The component of claim 48 comprising a single conductor, to accomplish an inductor.

50. The component of claim 48 comprising two co-linear conductors, to accomplish a transformer.

51. The component of claim 48 comprising three co-linear conductors, to accomplish a differential current transformer.

52. The component of claim 48 wherein the magnetic member and all conductors meander through a plurality of turns, to increase the component's effective length.

53. An angle measurement instrument for a rotating member having opposed flat faces, comprising:

a first pair of capacitive sensors proximate one face of said rotating member;

a second pair of capacitive sensors proximate the other face of said rotating member;

a planar differential current transformer proximate one pair of capacitive sensors, comprising:

two primary conductors, each comprising a single winding;

at least one secondary conductor comprising a single winding;

a single magnetic core member surrounding said primary conductors and said secondary conductor;

means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor;

means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor;

means for determining from the secondary conductor, the differential currents in the primary conductors, as a measure of the angle of said disk member to said capacitive sensors.

54. An angle measurement instrument for determining the angle of a rotating member having opposed faces, relative to fixed members comprising opposing, non-rotating flat faces, comprising:

a first pair of capacitive sensor plates fixed to one flat face proximate one face of said rotating member,

a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said rotating member,

wherein the rotating member rotates to change the gap between the rotating member and the fixed members;

a planar differential current transformer comprising:

a first conductor comprising one primary carrying current from one set of capacitive sensors;

a second conductor comprising a second primary carrying current from a second set of capacitive sensors, the sense of the second current being opposite that of the first current;

a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the rotating member;

a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length;

an insulator separating each conductor from any other conductor and all conductors from the magnetic core;

wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length;

wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length;

means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor;

means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and

means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the angle of said rotating member to said capacitive sensors.

55. An angle measurement instrument for determining the angle of a rotating member having opposed faces, relative to fixed members comprising opposing, non-rotating flat faces, comprising:

a first pair of capacitive sensor plates fixed to one flat face proximate one face of said rotating member,

a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said rotating member,

a planar differential current transformer comprising:

a first conductor comprising one primary carrying current from one set of capacitive sensors;

a second conductor comprising a second primary carrying current from a second set of capacitive sensors, the sense of the second current being opposite that of the first current;

a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the rotating member;

a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length;

an insulator separating each conductor from any other conductor and all conductors from the magnetic core;

wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length;

wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length;

means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor;

means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and

means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the angle of said rotating member to said capacitive sensors.

56. A translation measurement instrument for determining movement of a moving member having opposed faces, relative to fixed members comprising two opposing, fixed flat faces, comprising:

a first pair of capacitive sensor plates fixed to one flat face proximate one face of said moving member,

a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said moving member;

wherein the moving member moves to vary the gap between the moving member and the fixed members;

a planar differential current transformer comprising:

a first conductor comprising one primary carrying current from one set of capacitive sensors;

a second conductor comprising a second primary carrying current from a second set of capacitive sensors, wherein the sense of the second current is opposite that of the first current;

a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the moving member;

a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length;

an insulator separating each conductor from any other conductor and all conductors from the magnetic core;

wherein the properties of the transformer are obtained by establishing unit length

properties and meandering the single conductors with encircling magnetic

core to the desired length;

wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length;

means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor;

means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and

means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the translation distance of said moving member to said capacitive sensors.

57. A translation measurement instrument for determining movement of a moving member having opposed faces, relative to fixed members comprising opposing, fixed flat faces, comprising:

a first pair of capacitive sensor plates fixed to one flat face proximate one face of said moving member,

a second pair of capacitive sensor plates fixed to the second flat face proximate the other face of said moving member,

wherein the moving member moves relative to the fixed members;

a planar differential current transformer comprising:

a first conductor comprising one primary carrying current from one set of capacitive sensors;

a second conductor comprising a second primary carrying current from a second set of capacitive sensors, wherein the sense of the second current is opposite that of the first current;

a third conductor comprising a secondary carrying a current proportional to the difference between the first and second currents that vary in proportion to the motion of the translating member;

a magnetic core co-linear with and completely surrounding the conductors and whose length along the conductors determines the transformer length;

an insulator separating each conductor from any other conductor and all conductors from the magnetic core;

wherein the properties of the transformer are obtained by establishing unit length properties and meandering the single conductors with encircling magnetic core to the desired length;

wherein at any location along the length of the transformer, in cross section the transformer includes only one conductor for any conductive path, and the cross section is uniform with length;

means for electrically connecting one capacitive sensor from each pair in parallel to one primary conductor;

means for electrically connecting the other capacitive sensor from each pair in parallel to the other primary conductor; and

means for determining from the third conductor, the differential currents in the primary conductors, as a measure of the translation distance of said moving member to said capacitive sensors.

58. A method of fabricating an elongated, planar, generally linear electrical inductive component by multi-layered fabrication, the component having at least one conductor, each conductor in the component defining a unique conductive

path, a magnetic core co-linear with all conductors along the entire component length, and completely surrounding all conductors, and an insulator separating each conductor from any other conductor and all conductors from the magnetic core member, wherein at any location along the length of the component, in cross section the component includes only one conductor for any conductive path, and the cross section is uniform with length, the method comprising:

providing a lower layer of magnetic core material;

layering on top of the lower layer of magnetic core material, a second layer comprising a bottom insulator and first vertical segments of the magnetic core; wherein the first vertical segments of the magnetic core are in contact with the lower layer of magnetic core material;

layering on top of the second layer, a third layer comprising conductors and insulators, bounded on each side in the plane by second vertical segments of the magnetic core, the conductors separated from each other and from the second magnetic core vertical segments by a vertical insulator segment; wherein the second vertical segments of the magnetic core are located directly above and in contact with the first vertical segments of the magnetic core of the second layer;

layering on top of the third layer, a fourth layer comprising a top insulator and third vertical segments of the magnetic core, the third vertical segments of the magnetic core located directly above and in contact with the second vertical segments of the magnetic core;

layering on top of the fourth layer, a fifth layer comprising a top layer of magnetic core material that is in contact with the third vertical segments of the magnetic core.

59. The method of claim 58 comprising one conductor to accomplish an inductor.

60. The method of claim 58 comprising two co-linear conductors, each conductor defining a unique path, to accomplish a transformer.

61. The method of claim 58 comprising three co-linear conductors, each conductor defining a unique path, to accomplish a differential current transformer, wherein one conductor comprises one primary, the second conductor comprises a second primary and the third conductor comprises the secondary.

62. The method of claim 58 wherein the method of fabrication is by sequential deposition.

63. The method of claim 62 wherein the deposition comprises in part electroplating.

64. The method of claim 58 wherein the method of fabrication is by stacking and bonding of multiple layers formed separately.

PRIOR ART

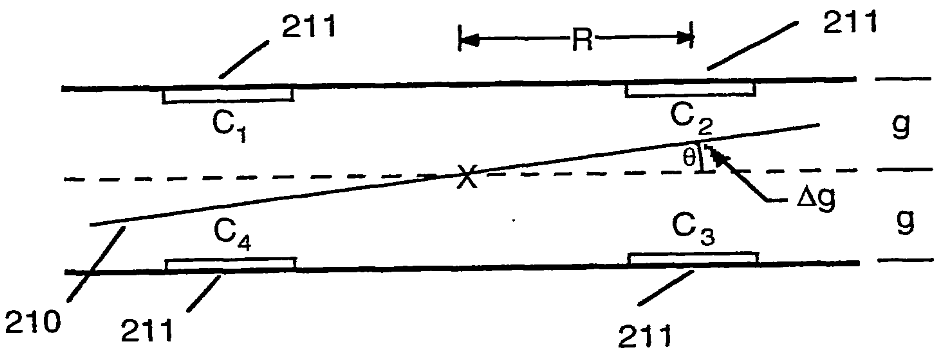


Figure 1

PRIOR ART

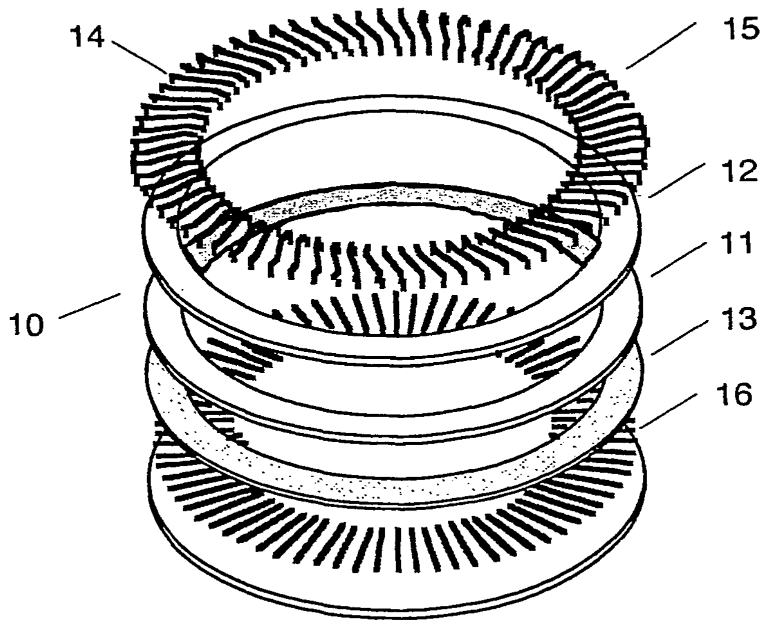


Figure 2

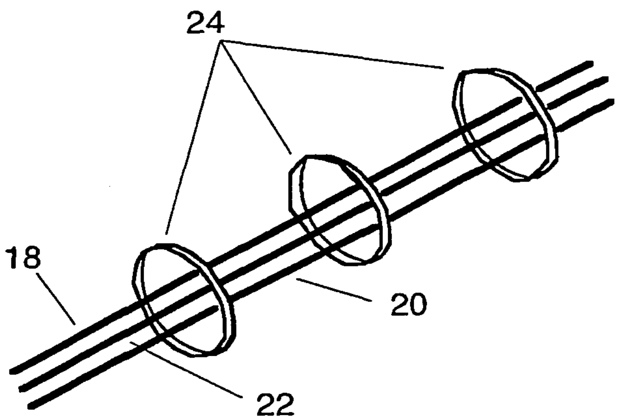


Figure 3

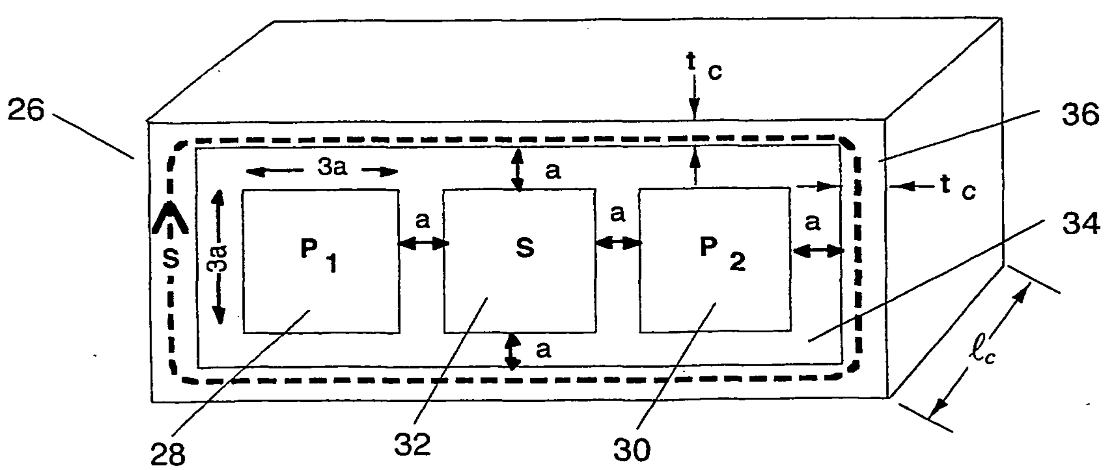


Figure 4

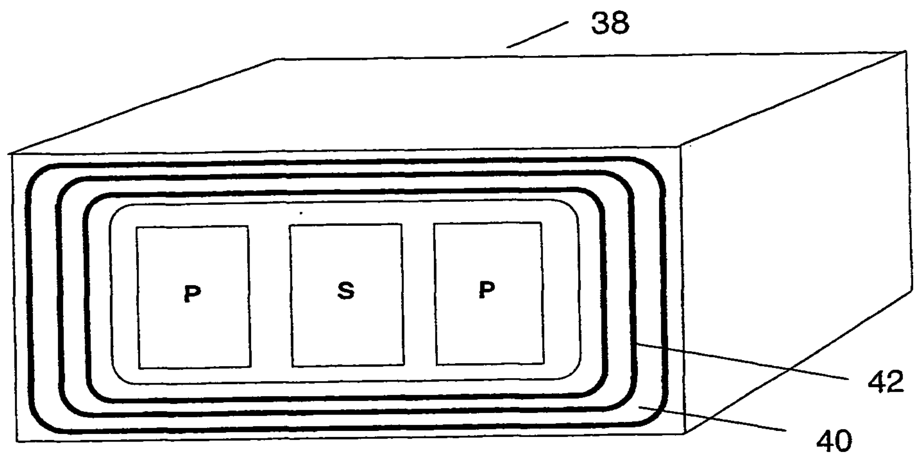


Figure 5

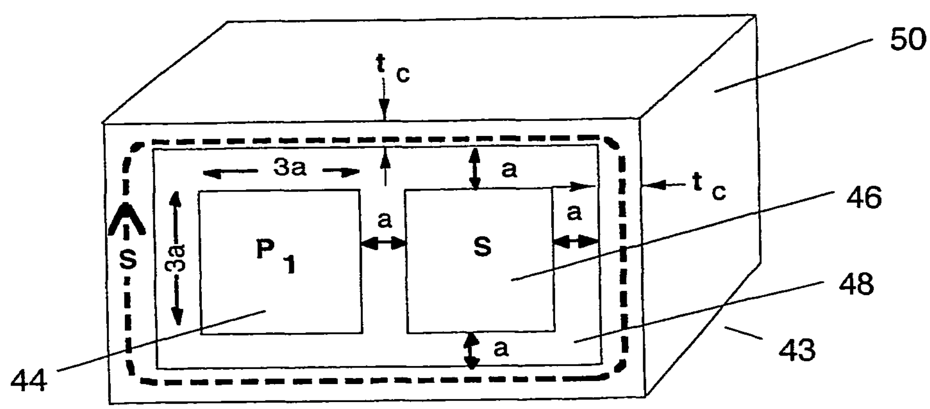


Figure 6

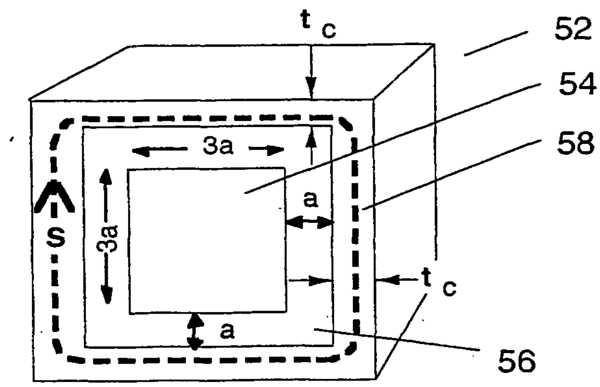


Figure 7

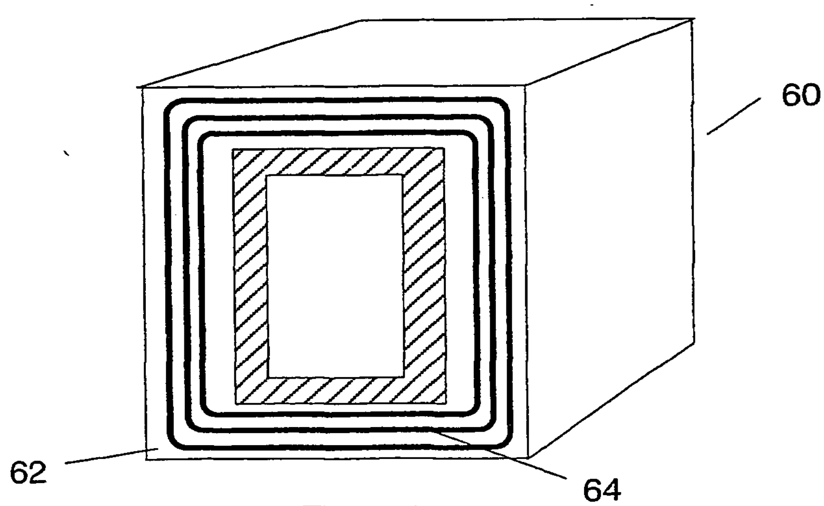


Figure 8

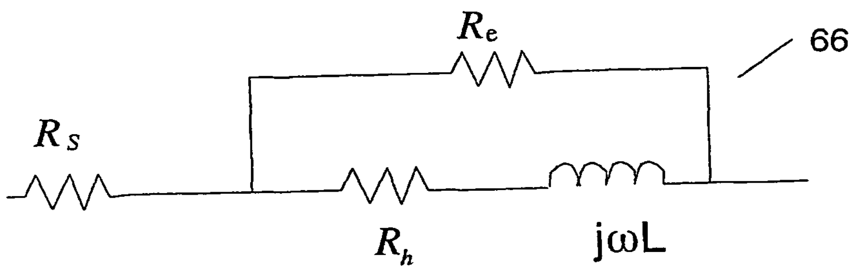


Figure 9

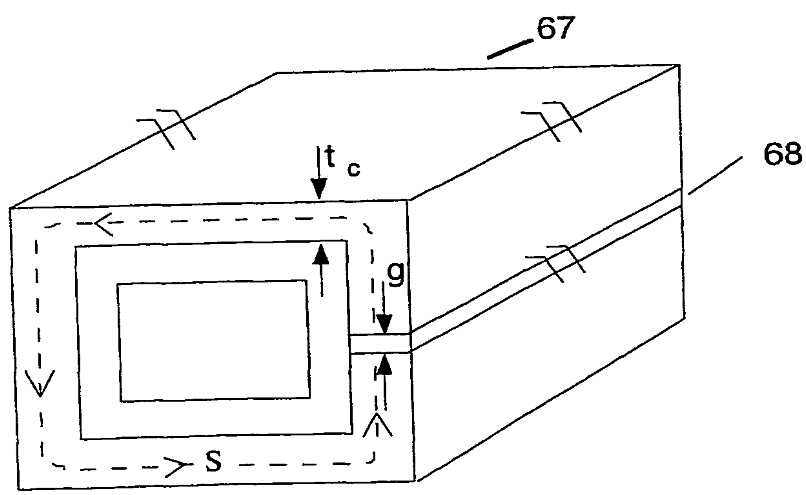


Figure 10

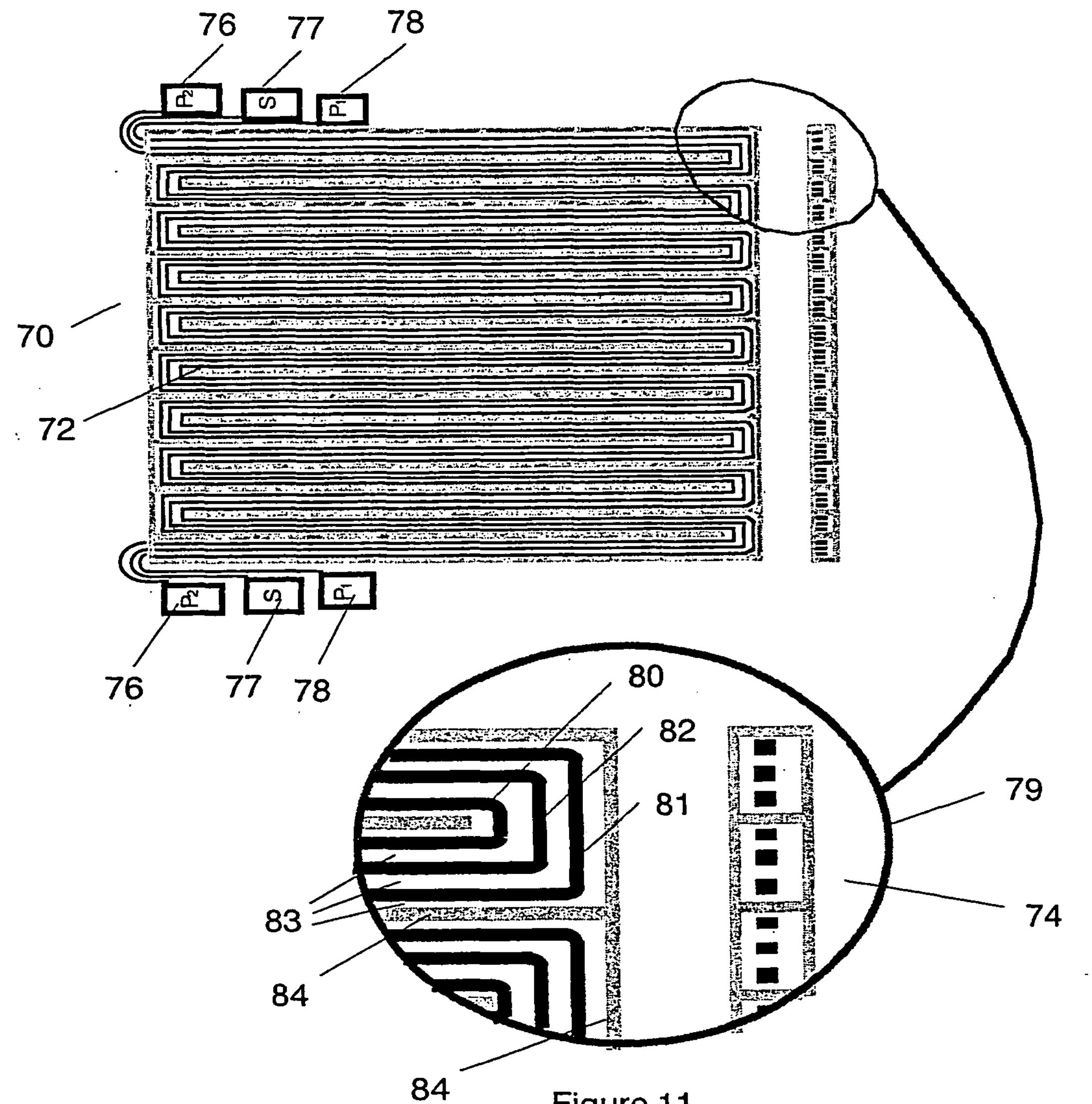


Figure 11

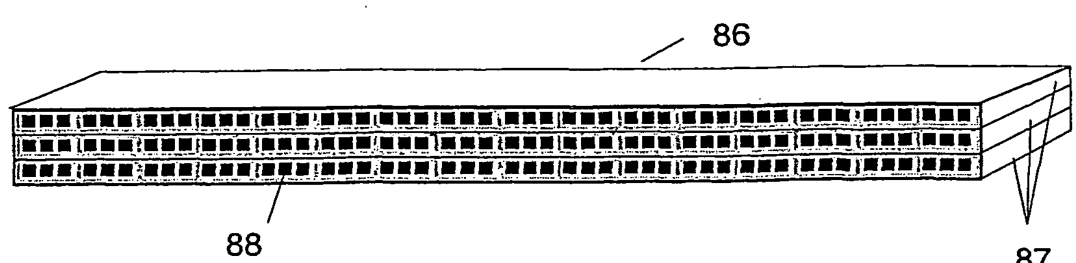


Figure 12

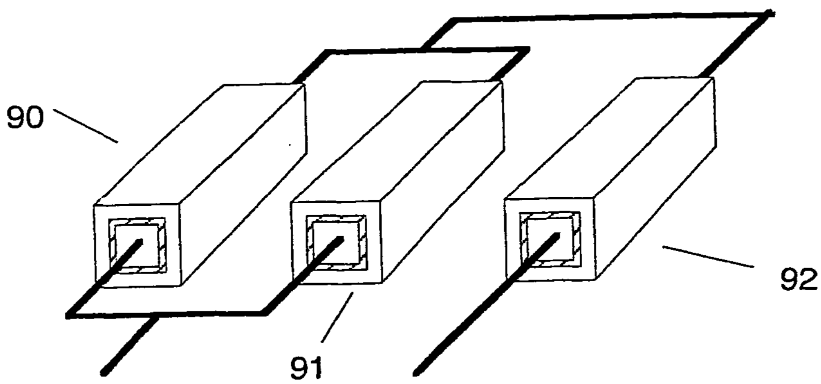


Figure 13

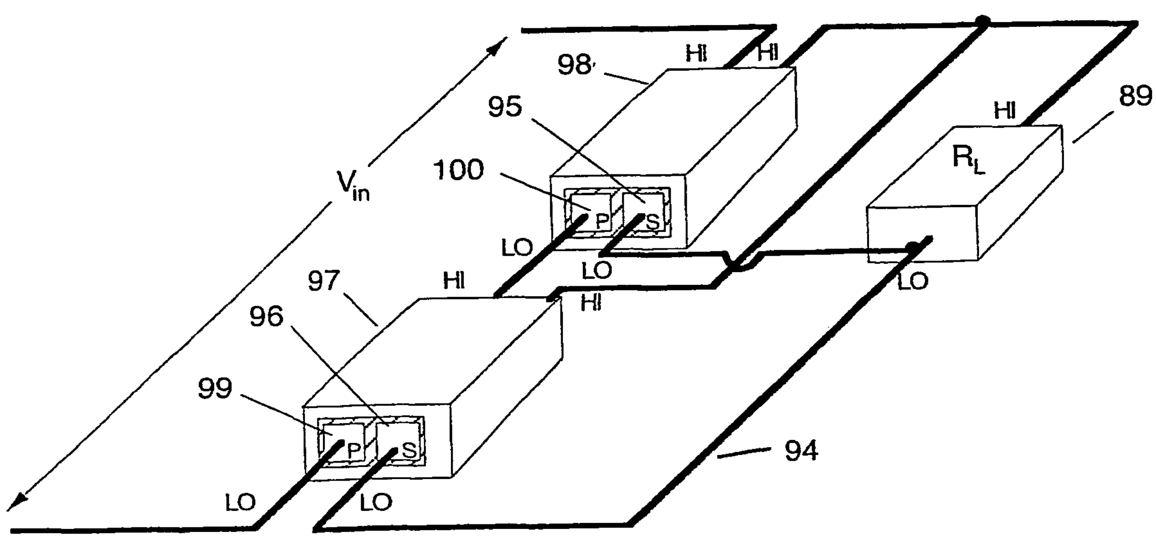
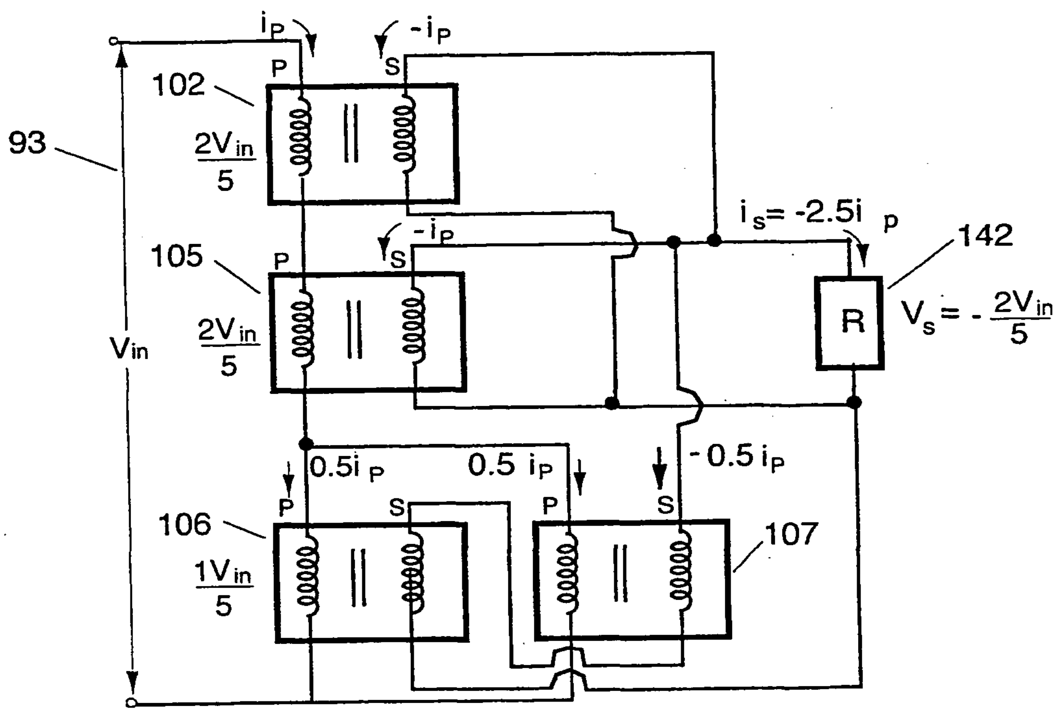


Figure 14



i_P
$-i_P$
P
S
102
93
$\frac{2V_{in}}{5}$
$i_s = -2.5i_P$
142
$-i_P$
105
P
S
$\frac{2V_{in}}{5}$
V_{in}
R
$V_s = -\frac{2V_{in}}{5}$
$0.5i_P$
$0.5\ i_P$
$-0.5\ i_P$
P
S
P
S
106
107
$\frac{1V_{in}}{5}$

Figure 15

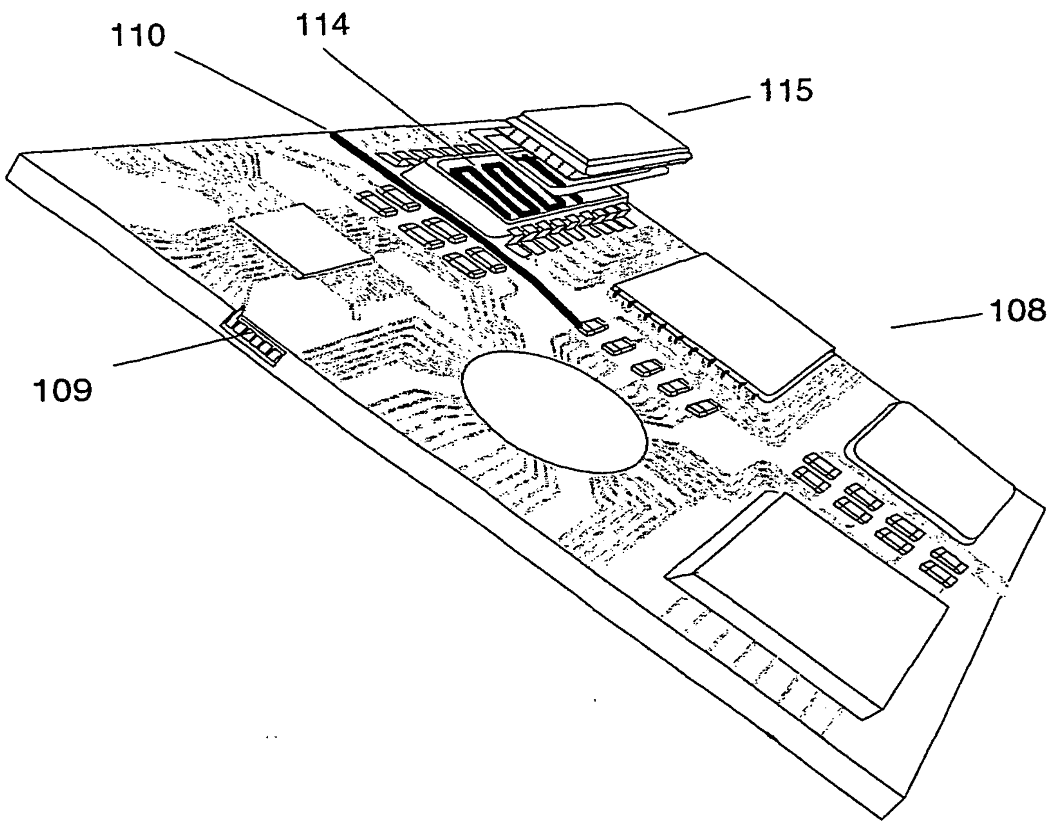


Figure 16

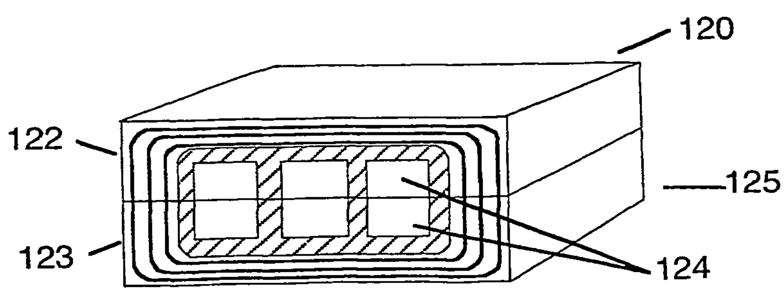


Figure 17a

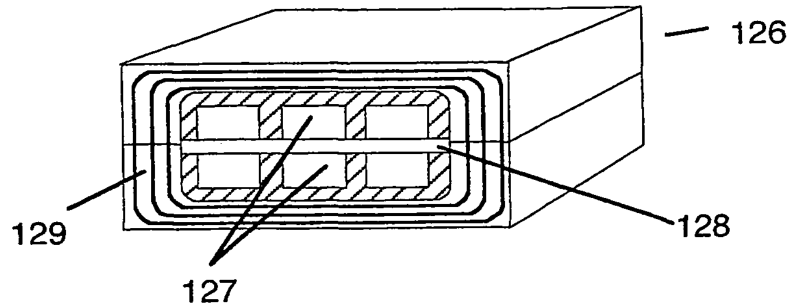


Figure 17b

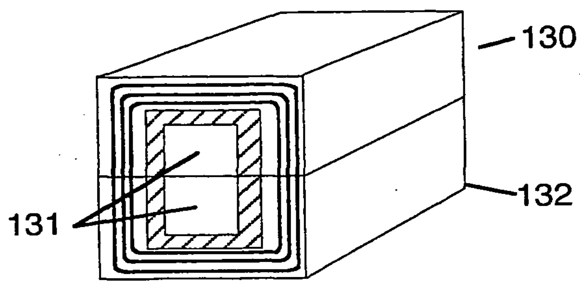


Figure 18a

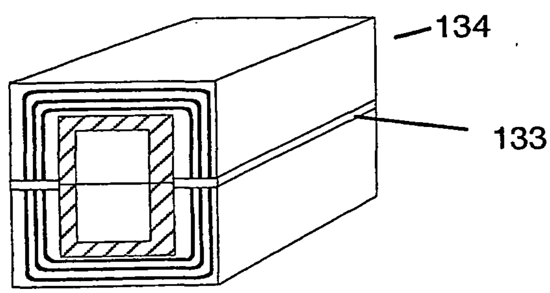


Figure 18b

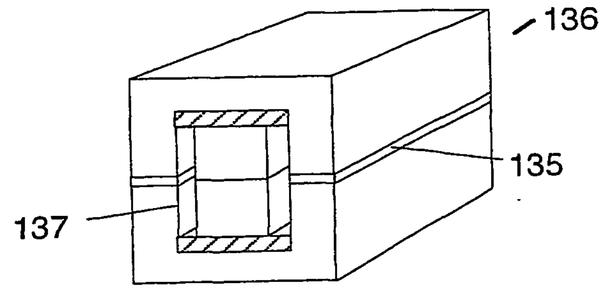


Figure18c

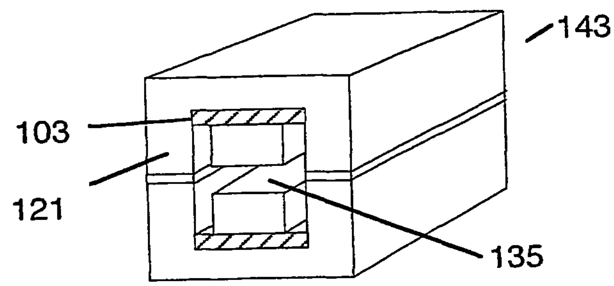


Figure 18d

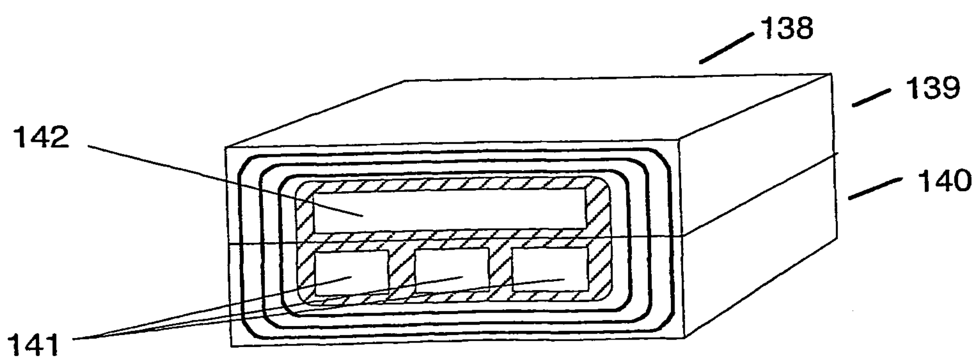


Figure 19

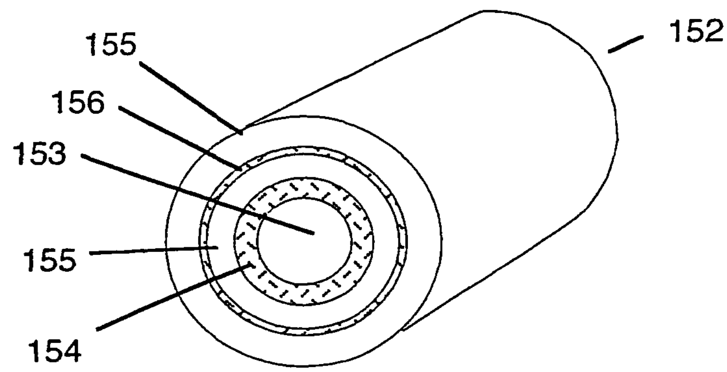


Figure 20

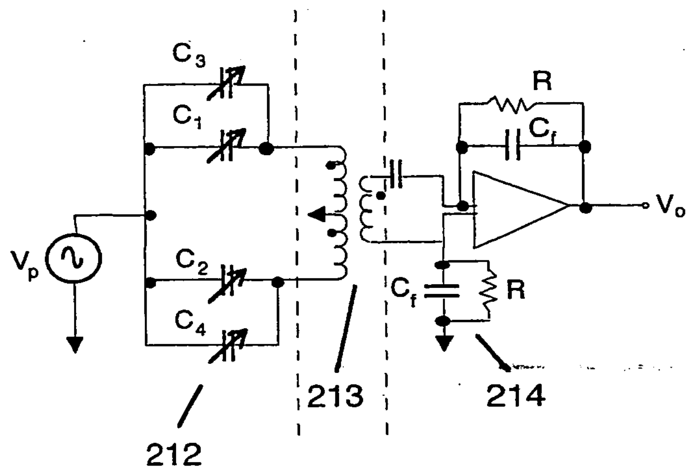


Figure 21a

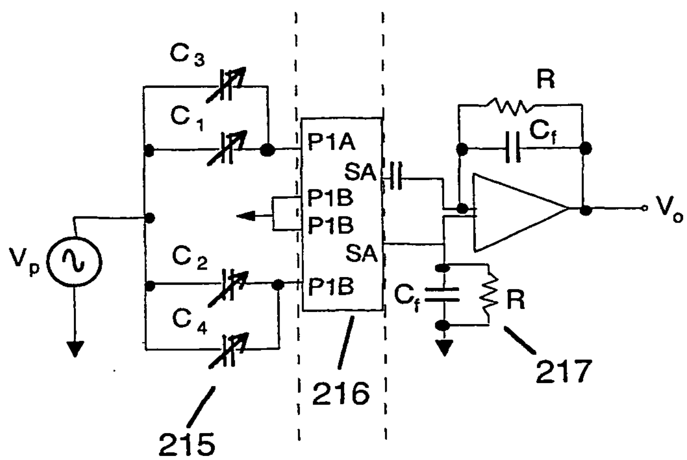


Figure 21b

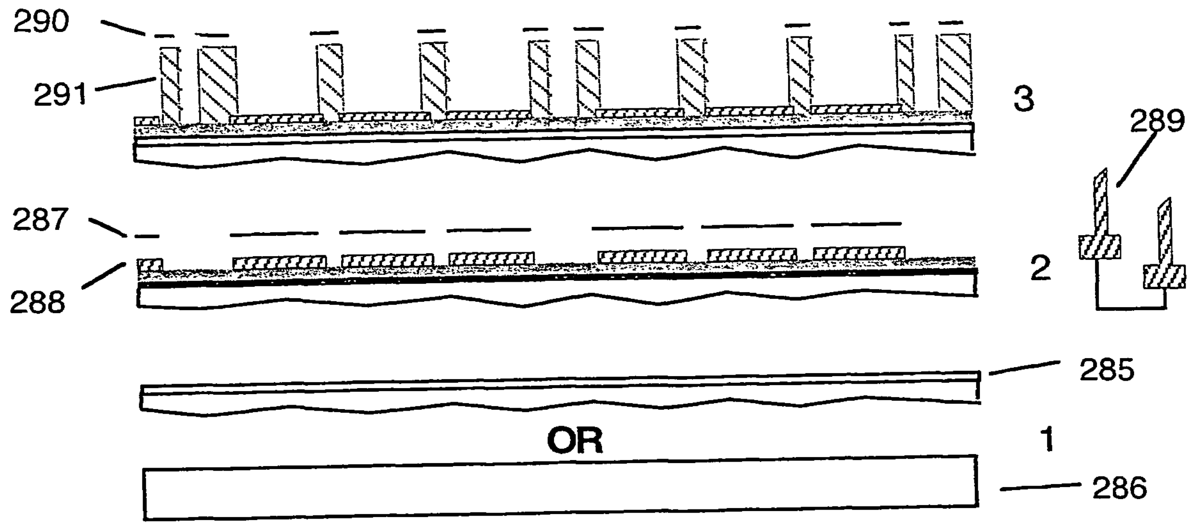


Figure 22a

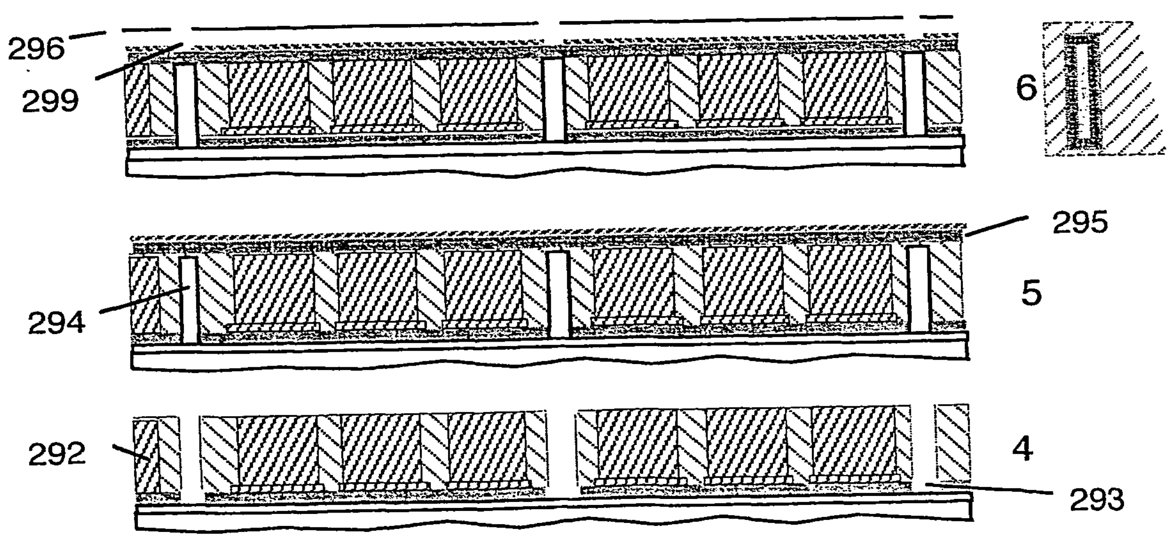


Figure 22b

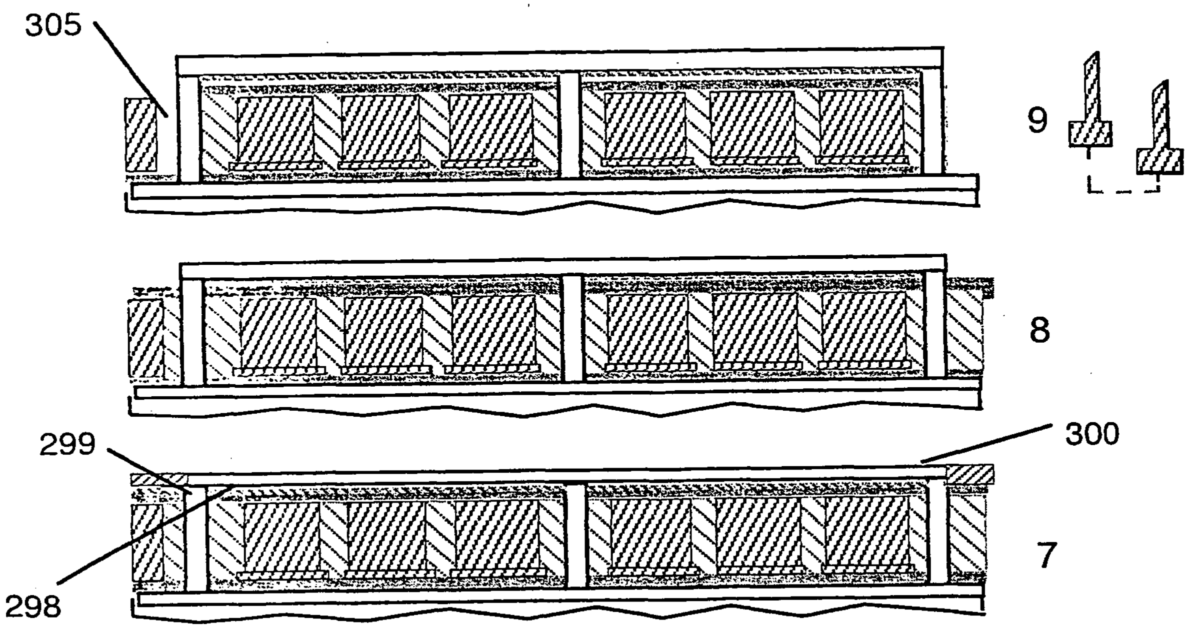


Figure 22c

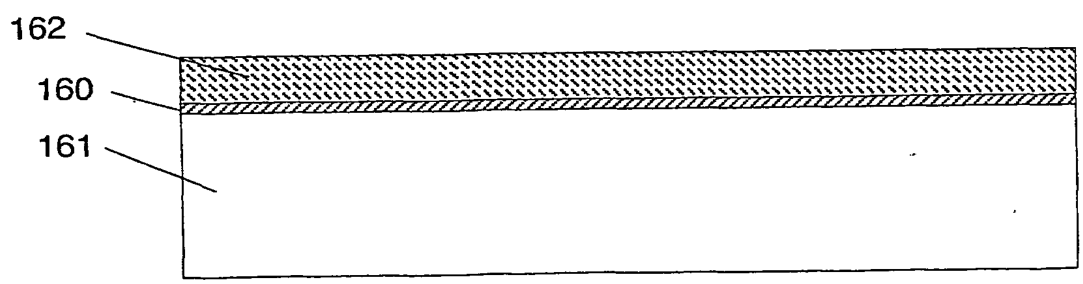


Figure 23a

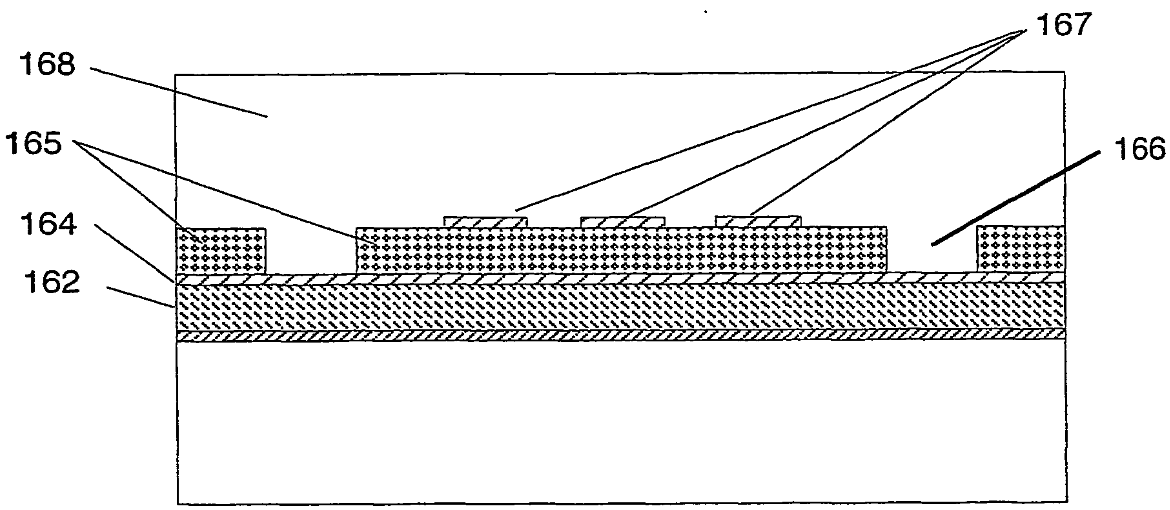


Figure 23b

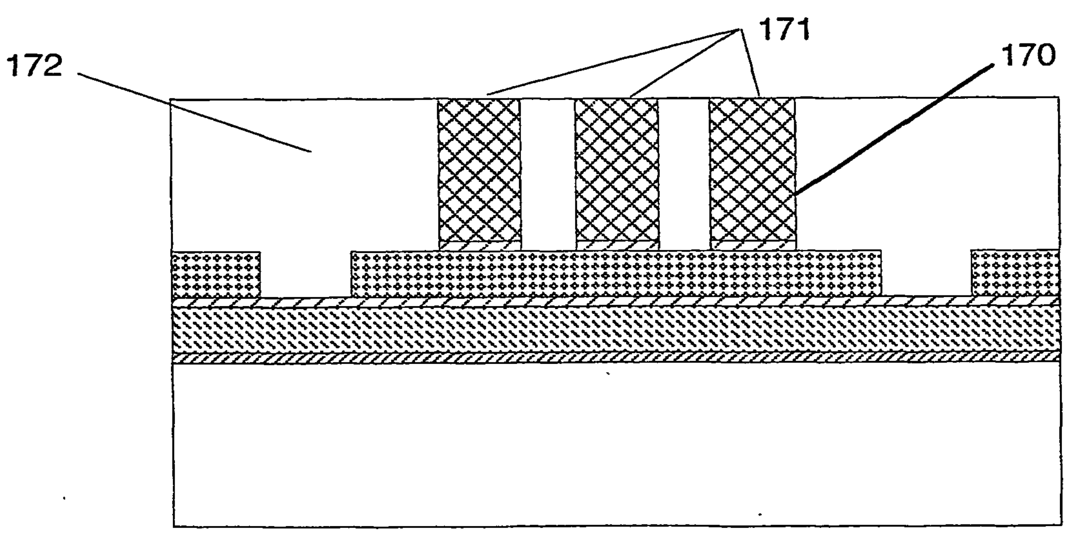


Figure 23c

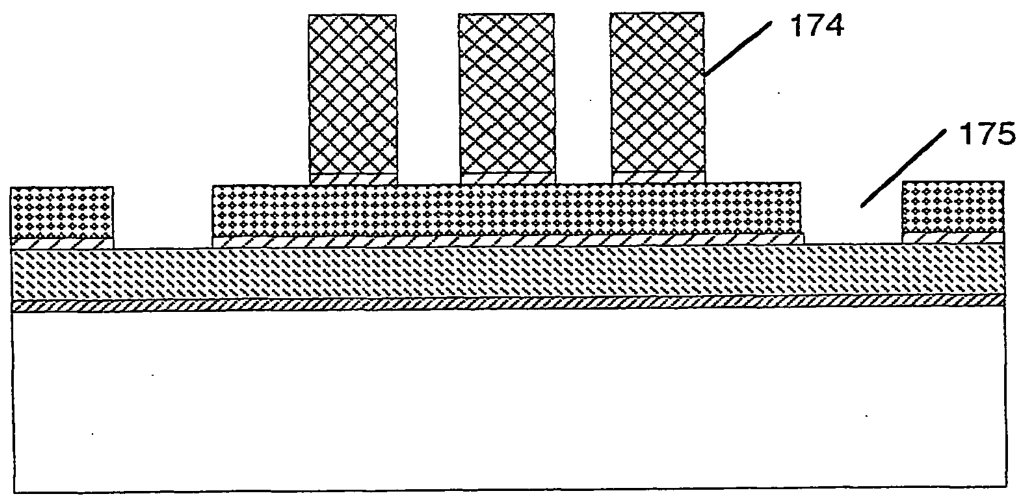


Figure 23d

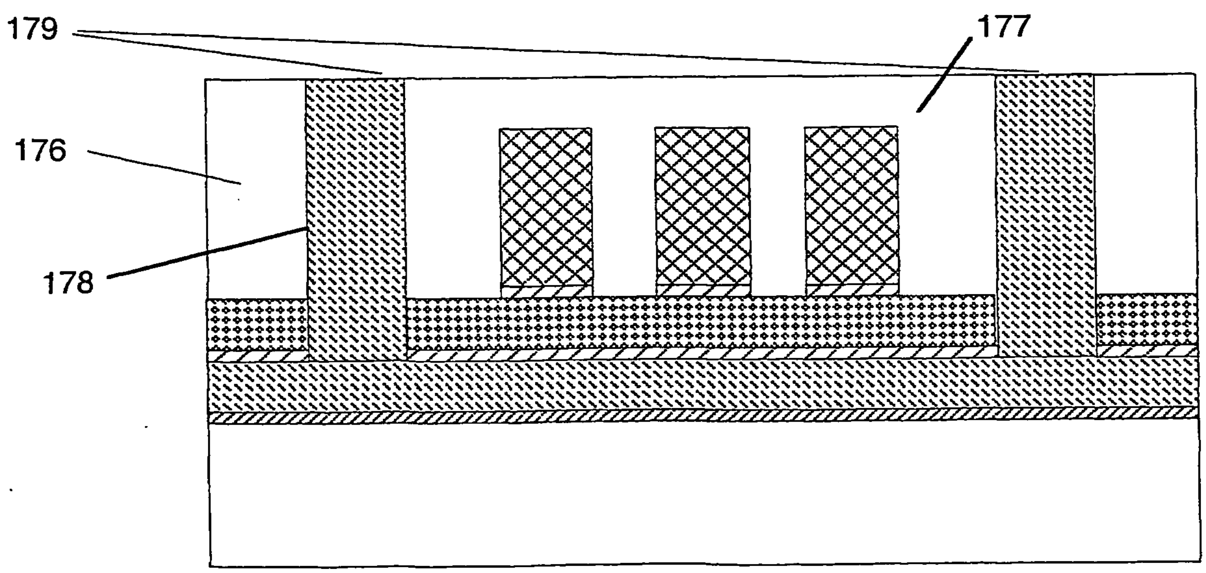


Figure 23e

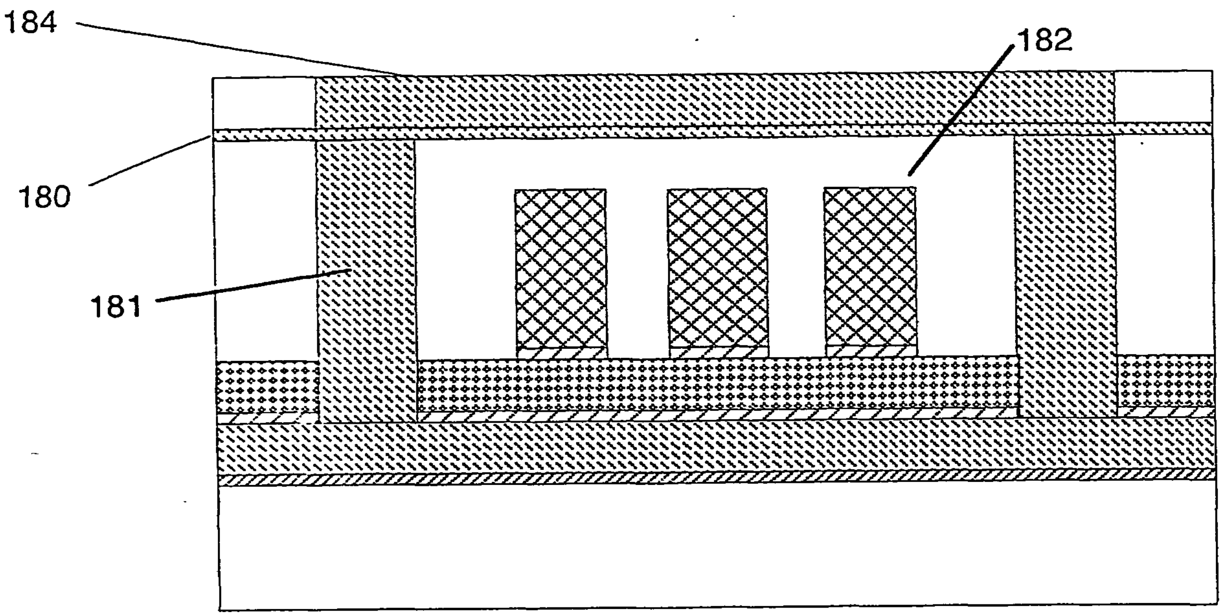


Figure 23f

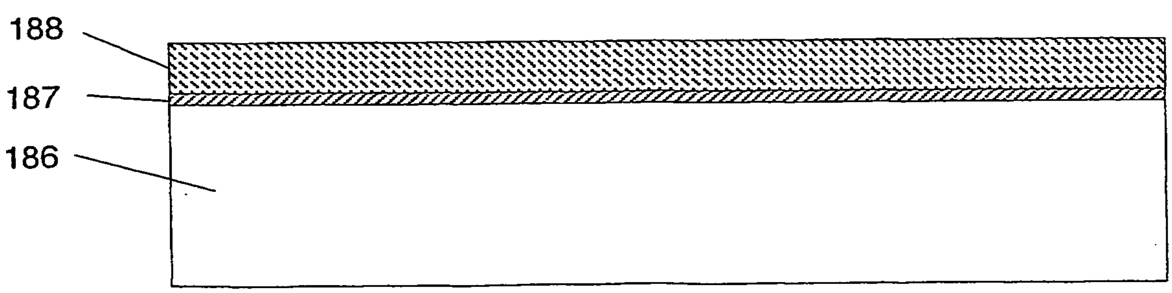


Figure 24a

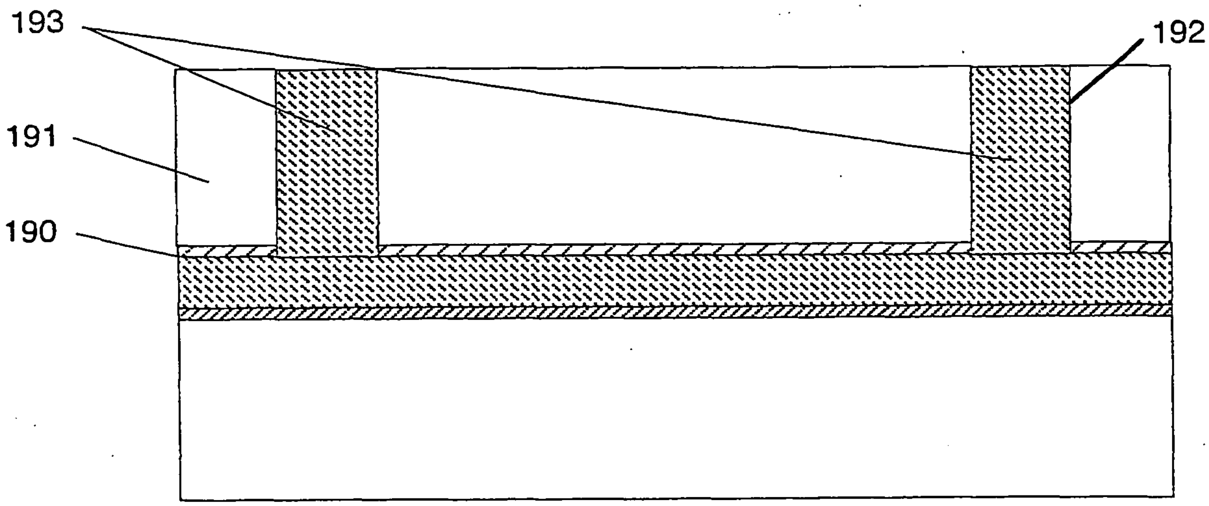


Figure 24b

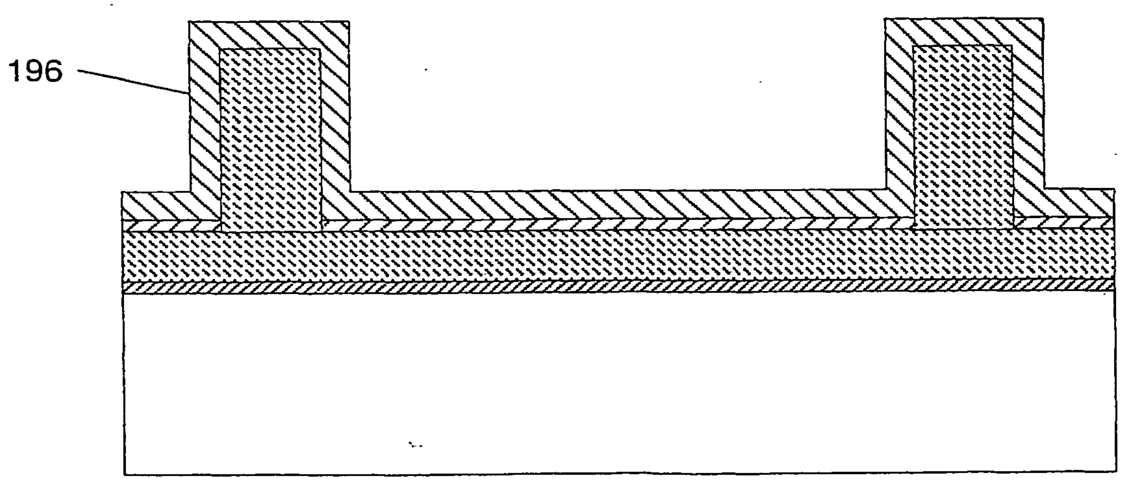


Figure24c

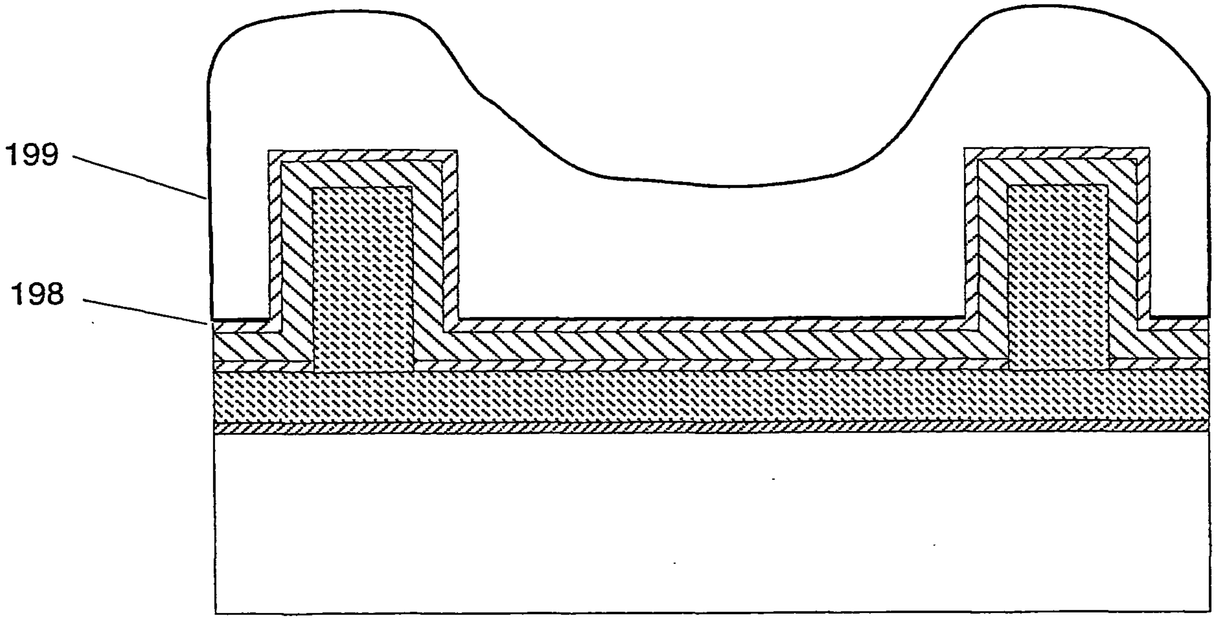


Figure 24d

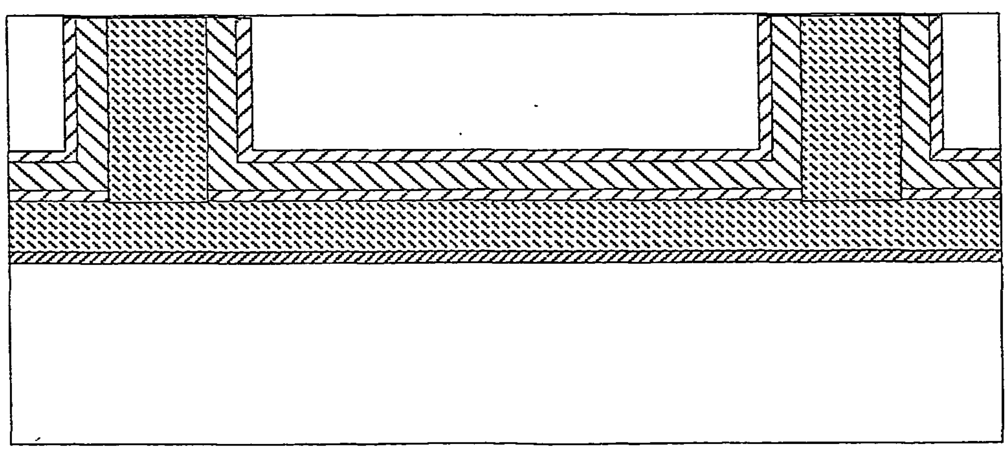


Figure 24e

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/16428

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01F 7/06; H01F5/00; G01R 1/02
US CL : 29/602.1, 606; 336/60, 100, 175, 180, 184, 223; 324/127
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 29/602.1, 606; 336/60, 100, 173-175, 180, 182, 184, 223; 324/127; 33/1PT, 1N, 534

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST: capacitive sensor, conductor, lamination, electroplating, photolithography, insulator.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,853,617 [DOUGLAS ET AL.] 01 AUGUST 1989 (01.08.1989)	1-64
A	US 5,892,365 [BAILLEUL ET AL.] 06 APRIL 1999 (06.04.1999)	1-64
A	US 3,665,356 [DOUGLAS ET AL.] 23 MAY 1972 (23.05.1972)	1-64
A	US 1,866,751 [W. BUTOW] 12 JULY 1932 (12.07.1932)	1-64
A	US 5,263,258 [DOBLER ET AL.] 23 NOVEMBER 1993 (23.11.1993)	1-64
A	US 5,737,211 [HIRAI ET AL.] 07 APRIL 1998 (07.04.1998)	1-64

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 07 AUGUST 2001	Date of mailing of the international search report 04 SEP 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer ANH T. MAI Telephone No. (703) 308-2900